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13. ABSTRACT (Maximum 200 words)

**The long term goal of this study is to provide a fundamental understanding of the** liquefaction behavior of a multiphase particulate material consisting of gravel, sand, and silt at both macroscopic and microscopic levels. Liquefaction of saturated soils has often been a major cause of damage to earth embankments and buildings. The cyclic behavior of stratified gravel-sand-silt composites is presently poorly understood, yet these materials are commonly found in alluvial deposits and hydraulic fill, which have a history

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of liquefaction. The main objective of this research project was to compare the behavior of stratified and homogeneous sand-silt-gravel composites at the macroscopic level during seismic liquefaction conditions for various silt and gravel contents. A preliminary experimental program was undertaken in which a total of fifty stress-controlled undrained cyclic triaxial tests were performed. Two methods of sample preparation were used for each soil type. These methods included moist tamping (representing uniform soil conditions) and sedimentation (representing layered soil conditions). The silt contents ranged from 0 to 50 percent, and soils with 10% and 30% gravel contents were tested. The confining pressure in all test series was 100 KPa. The following primary conclusions were obtained as a result of this study.

1. The liquefaction resistance of layered and uniform soils are not significantly different, despite the fact that the soil fabric produced by the two methods of sample preparation is totally different. This finding justifies applying the laboratory tests results to the field conditions for the range of variable studied.

2. The increase in silt content (percent passing No. 200 sieve) causes the liquefaction resistance of sand-silt-gravel mixtures to increase for both uniform and layered soil conditions.

More research is needed to confirm these findings for a wide range of variables including confining pressures, gravel contents, and anisotropic soil conditions. In addition, investigation of microstructural features of stratified soils and their relations to the dynamic macro behavior will help to provide further understanding of behavior of layered soils.

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# MICROSTRUCTURE FEATURES AND DYNAMIC MACRO-BEHAVIOR OF A MULTIPHASE PARTICULATE MATERIAL

## 1. INTRODUCTION

Most previous research on liquefaction have been focused on uniform clean sands, or sands with little fines. However, A number of case histories have indicated that gravels and gravely soils can also liquefy (e.g., Harder and Seed, 1986; Wang, 1984; Tamura and Lin, 1983; Youd et al., 1985; Andrus et al., 1986; and Evans and Harder, 1993). As a result, evaluation of liquefaction potential of gravels and gravely soils has become a high priority in the geotechnical seismic engineering community. In recent years, the liquefaction behavior of gravels has been experimentally studied in the laboratory by several researchers (e.g., Nicholson et al., 1993a and 1993b; Evans, 1992; Evans et al. 1992; Seed et al., 1989; Hynes, 1988; and Benerjee et al. 1979). The liquefaction behavior of sand-gravel composites have been studied by Evans and Zhou (1995), Siddiqi (1984), Wang (1984) and Haga (1984). Evans and Zhou (1995) concluded that the liquefaction resistance of sand-gravel composites increased significantly with increasing gravel content. They also proposed a methodology to estimate the cyclic strength of the composite soil by testing the sand fraction alone.

To date an understanding of the liquefaction behavior of stratified contractive undrained sand-silt-gravel composites is lacking. In this study, the behavior of such soils was systematically investigated considering the effect of gravel and silt content. Stratified soils exist in the field where various soil types have been deposited through water by nature (alluvial, lacustrine, marine deposits) or by man (hydraulic fills). It is known from past observations that these types of soil deposits often experience liquefaction.

# 2. STATEMENT OF THE PROBLEM

## 2.1 Background

Almost all laboratory seismic liquefaction studies have dealt with homogeneous soil conditions only, although stratified fine soils exist for various soil deposits. A limited study of behavior of layered silty sands was performed by Dobry and his coworkers (Vasquez-Herrera and Dobry, 1989). After examination of the results for two different sample preparation methods, namely moist tamping (representing homogeneous soil conditions) and sedimentation (representing stratified soil conditions), they concluded that the behavior of layered and homogeneous soils are not significantly different in terms of the triggering relationships, despite the fact the sand fabric produced by these two methods was totally different. This observation has been summarized by Marcuson, Hynes, and Franklin of U.S. Army Waterways Experiment Station (Marcuson, et al., 1990).

In addition, the behavior of layered sand-silt soils have been recently studied using centrifuge model tests (Fiegel and Kutter, 1992) through research projects sponsored by National Science Foundation and the Naval Civil Engineering Laboratory. The layered soil model consisted of fine sand and was overlain by a relatively impermeable silt. Pore-water pressures, accelerations, and settlements were measured during the tests. Results from the model tests involving layered soils suggested that during liquefaction a water interlayer or very loose zone of soil may develop at the sand-silt interface due to the difference in permeabilities. In the layered tests, boils were observed on the surface of silt layer. These boils were concentrated in the thinnest zones of the overlaying silt layer and provided a vent for the excess pore-water pressure generated in the fine sand. No liquefaction flow failure was noted during centrifuge tests studies.

## 2.2 Objectives of the Proposed Study

The primary objective of this study was to compare the behavior of stratified and homogeneous silt-sand-gravel composites during seismic liquefaction. Silt content in the range of 0 to 50 percent, and two different gravel content (10% and 30%) have been considered.

## 3. EXPERIMENTAL PROCEDURES

### 3.1 Soils Tested and Variables Studied

To accomplish the objectives of this study, silt, sand, and gravel were obtained from commercial sources. The maximum size of gravel particles was 10 mm (3/8 in). The ratio of the specimen diameter (2.8 in) to particle size (3/8 in) is approximately 7.5. A ratio of 6 to 8 is usually required for accurate test results. Two series of gravely soils with different sand and silt contents were used. Series 1 and 2 consisted of soils with 30% and 10% gravel, respectively. The silt content for these series (percent passing No. 200 sieve) ranged from 0 to 50 percent. The soils properties for the soils used during this study are shown in Tables 1a and 1b. The silt-sand-gravel mixtures were prepared by mixing appropriate amounts of Ottawa 20-30 sands, gravel, and low plasticity silt. The silts had a liquid limit of approximately 35, and a plasticity index of about 13. The grain size distribution curves for the soils are shown in Figures 1a and 1b. The target relative density was 50%. In this study, soil specimens were isotropically consolidated under a confining pressure of 100 Kpa. The term "liquefaction" as used in this report refers to the state in soils where the effective pressure has decreased and reached zero, shifting all of the confining pressure to the pore water. Because the gravel content was relatively low, no membrane correction was considered as part of this study (Evans, et al., 1992).

### 3.2 Equipment

For the purpose of performing the stress-controlled cyclic triaxial tests, the Automated Triaxial Testing System, developed by C. K. Chan, was used (Li, et al., 1988). A schematic of the Automated Triaxial Testing System at the University of the District of Columbia is shown in Figure 2, and a photograph of a soil sample after liquefaction is shown in Figure 3. This system is capable of performing both static and dynamic testing. In the automated system the computer programmed electronic signals for frequency and magnitude of loading are applied to an electro-pneumatic transducer that then controls pneumatic amplifiers for the application loading. Two

Table 1a. Properties of Soils Tested – Series 1

| Group | Percent Gravel | Percent Silt * | Percent Sand | $G_s$ | $D_{50}$ (mm) | $C_u$ | $\gamma_{max}$ (pcf) | $\gamma_{min}$ (pcf) |
|---|---|---|---|---|---|---|---|---|
| 1A | 30 | 0 | 70 | 2.63 | 0.70 | 1 | 116.2 | 107.0 |
| 1B | 30 | 25 | 45 | 2.63 | 0.70 | 60 | 133.8 | 101.7 |
| 1C | 30 | 50 | 20 | 2.62 | 0.60 | 310 | 127.2 | 76.6 |

*Silt : LL=35 PI=13

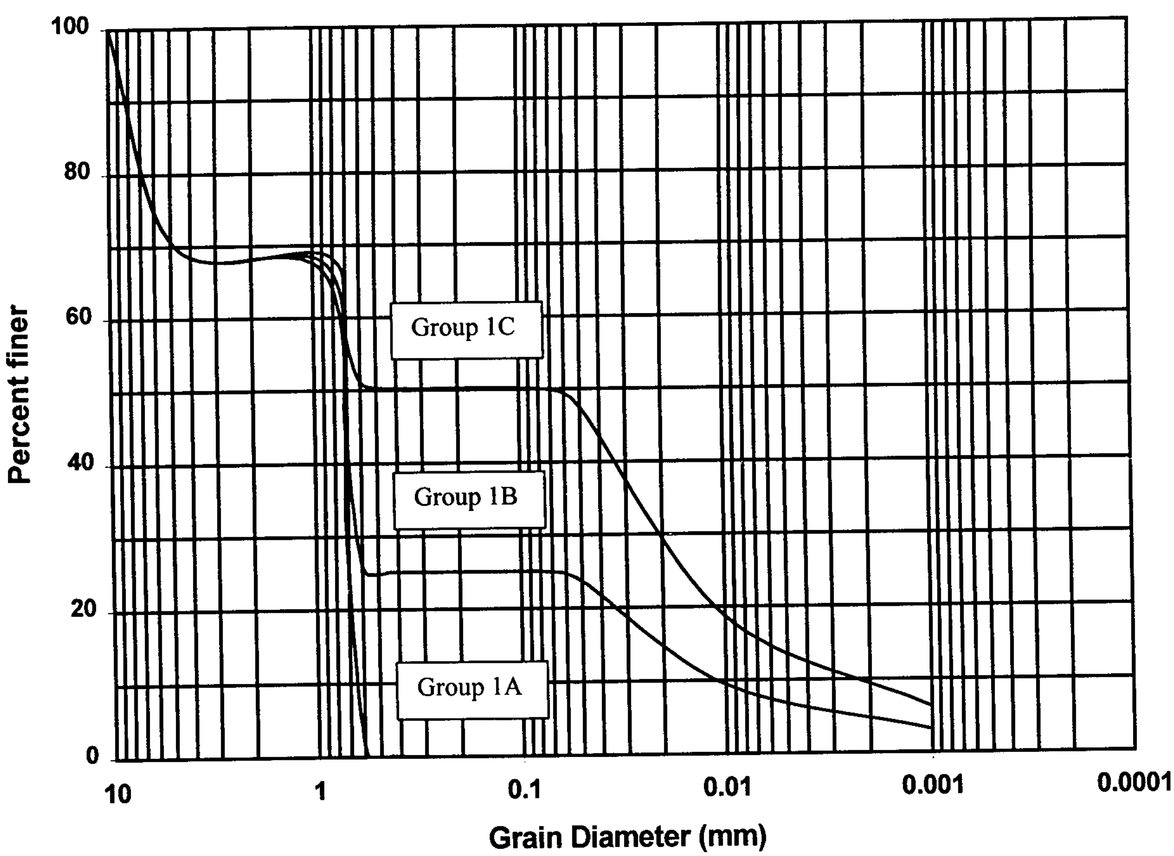


Figure 1a. Grain Size Distribution for Soils Tested – Series 1

Table 1b. Properties of Soils Tested – Series 2

| Group | Percent Gravel | Percent Silt * | Percent Sand | $G_s$ | $D_{50}$ (mm) | $C_u$ | $\gamma_{max}$ (pcf) | $\gamma_{min}$ (pcf) |
|---|---|---|---|---|---|---|---|---|
| 2A | 10 | 0 | 90 | 2.64 | 0.70 | 1 | 110.1 | 101.0 |
| 2B | 10 | 25 | 65 | 2.63 | 0.70 | 60 | 121.4 | 90.8 |
| 2C | 10 | 50 | 40 | 2.63 | 0.60 | 310 | 117.3 | 73.7 |

*Silt : LL=35 PI=13

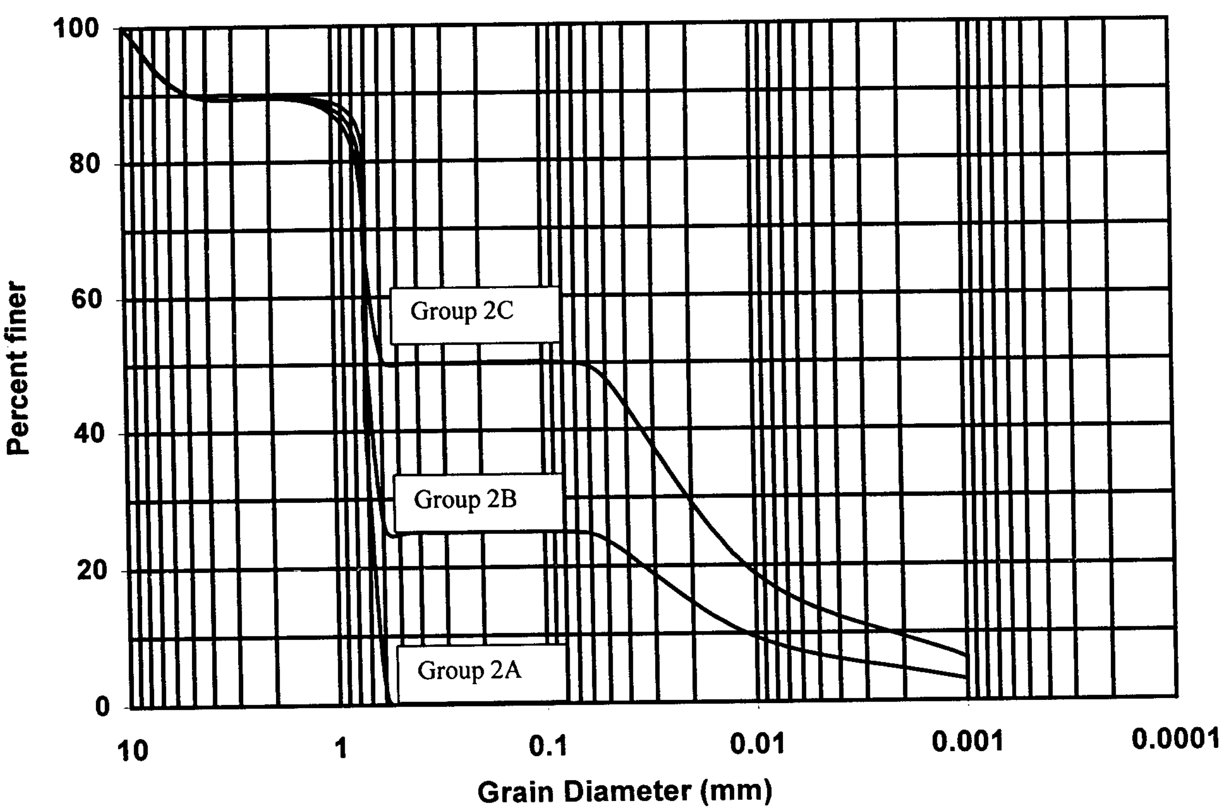


Figure 1b. Grain Size Distribution for Soils Tested – Series 2

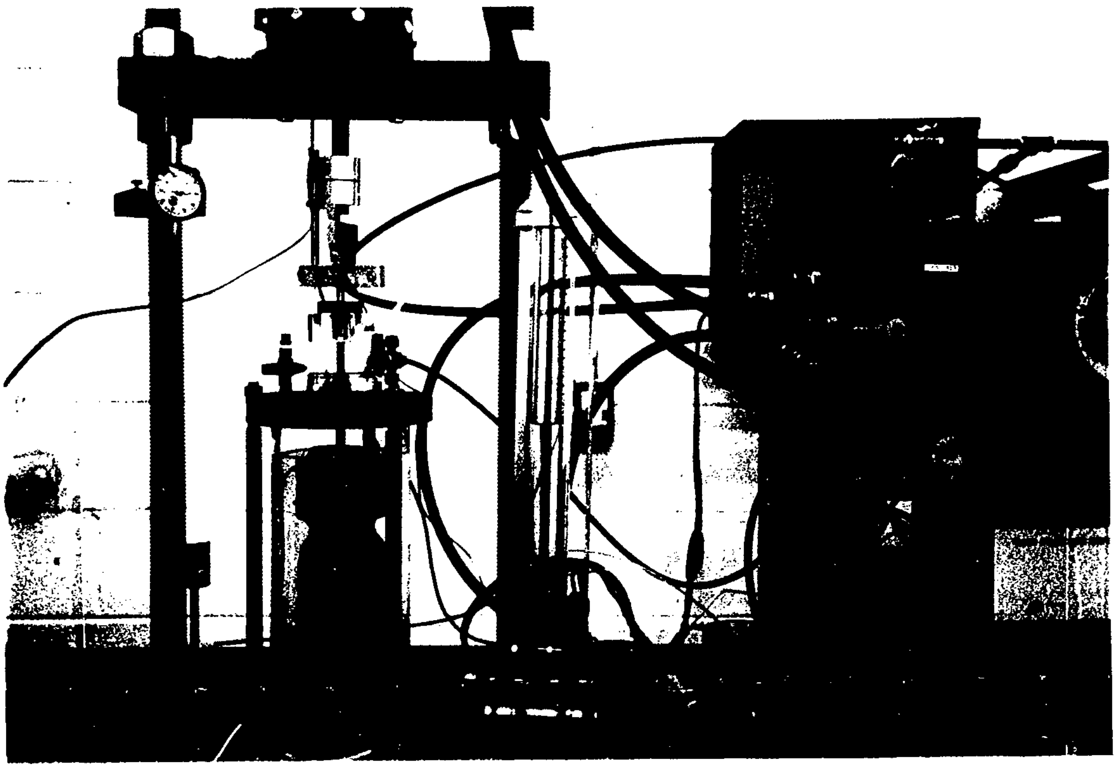

Figure 2. Schematic of the Automated Triaxial Testing System at the University of the District of Columbia

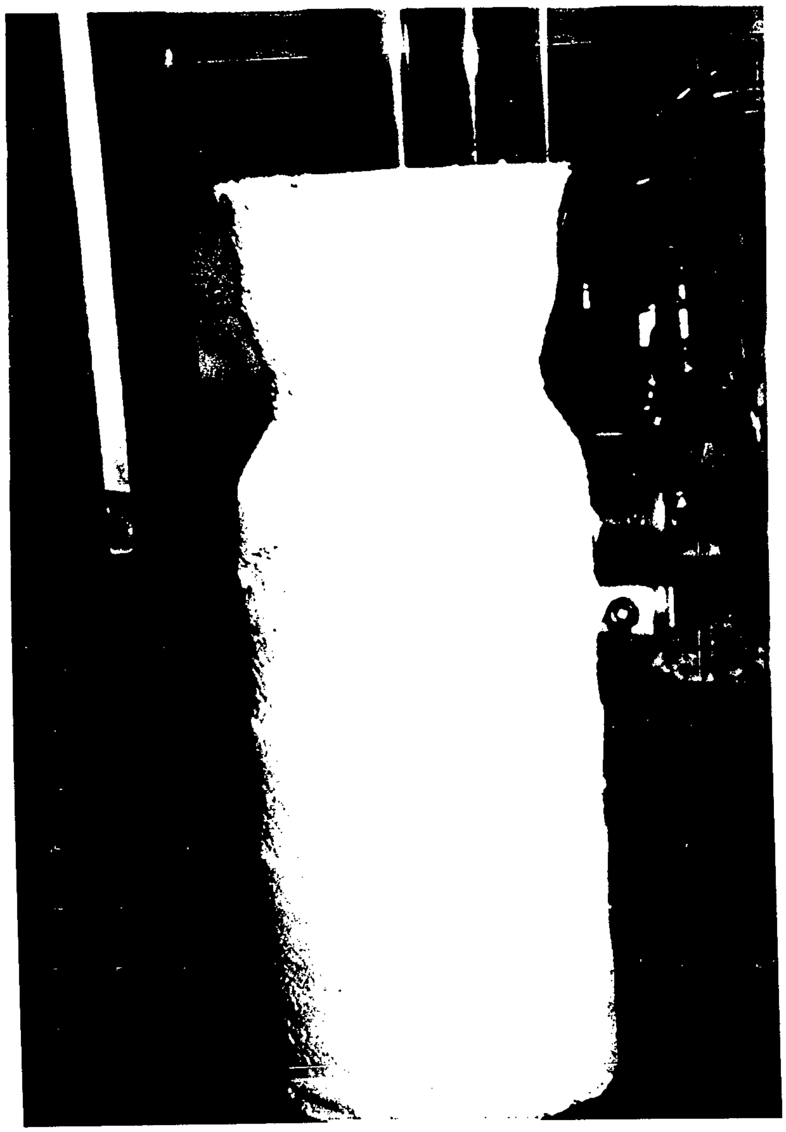

Figure 3. Photograph of Soil Specimen After Liquefaction

control channels allow the independent and synchronized adjustment of the axial load and chamber pressure. The computer controls the whole system, receiving and storing the real time data in its memory and issuing control signals to conduct the required tests. The software includes a number of applications, such as back pressure saturation, consolidation, shear loading, and cyclic loading.

**3.3 Methods of Sample Preparation**

Two methods of sample preparation were utilized for each soil type. These methods included moist tamping (representing homogeneous soil conditions) and the wet pluviation (representing layered soil conditions). The methods are described below.

The first method was the moist tamping using an undercompaction procedure (Ladd, 1977; Ladd 1978) which simulated a homogeneous soil condition. The procedure incorporated a tamping method of compacting moist soils in layers. Each successive layer was compacted to an increased percentage of the required unit weight of the specimens. The procedure consisted of pouring increasing amounts of soils (by weight) for constant height successive layers. Using this method, the compaction of each succeeding layer could further densify the sand below it, and therefore a uniform specimen was obtained. To avoid densification, water was added to give the sample strength through capillary stresses. The soil mixtures were usually poured in layers and tamped using specified weights.

The second method involved the use of wet pluviation (sedimentation) procedure to simulate layered soil conditions. Using this method, the mold with a stretched membrane was filled with deaired water. Soil layers (typically seven layers) were then constructed by pouring equal weights of soil and waiting for at least one hour for sedimentation. Because of the different settling rates of coarse and fine grains, the most coarse-grained portion settles at the bottom and grades to fines at the top within each layer. Specimens with varying void ratios could be prepared by this method.

## 4. RESULTS

### 4.1 Effect of Silt Content

The effect of silt content on the liquefaction behavior is shown in Figures 4 through 7. The liquefaction resistance of silty sands generally increased with increasing silt content for both uniform and layered soils conditions and for different gravel contents. For homogeneous soils in series 1 (30% gravel), a change in silt content from 25 to 50 % caused a 23% increase in the cyclic stress ratio causing liquefaction in 10 cycles. The same change in silt content caused a 16% increase in homogeneous samples of series 2 (10% gravel). The results of this study is in general agreement with previous results for uniform soils that the presence of fine contents generally increases the liquefaction resistance (e.g., Chang, 1987; Kaufman, et al 1982; and Yeh, 1981). As the silt content increases, sand particles are increasingly surrounded by silt, and the sand-grain-to-sand-grain (or gravel) contact decreases. As a result, the specimen behavior becomes somewhat more similar to silty soils. It should also be noted that although the effect of increase in silt content is to increase the liquefaction resistance, for the whole system, taking into account such factors as redistribution of void ratios, and pore water pressure migration, the silt content effect may be different from that of a given specimen. The results of this study also indicate that the effects of silt content are similar for both homogeneous and layered soils.

### 4.2 Comparison Between Layered and Uniform Soil Conditions

Examples of comparison between the liquefaction behavior of layered and uniform soils are shown in Figure 8 through 13 for series 1A through 1C (30% gravel content) and 2A through 2C (10 % gravel content). The comparison is shown in Figures 14 through 15, as a function of silt content. The results generally indicated that the liquefaction resistance of layered and uniform soils was not significantly different, despite the fact that the soil fabric produced by the two methods of sample preparation was totally different. This behavior was observed under a wide range of silt contents. For soils of series 1 (30% gravel), the difference in resistance to liquefaction between layered and uniform soils decreased as the number of cycles increased. For

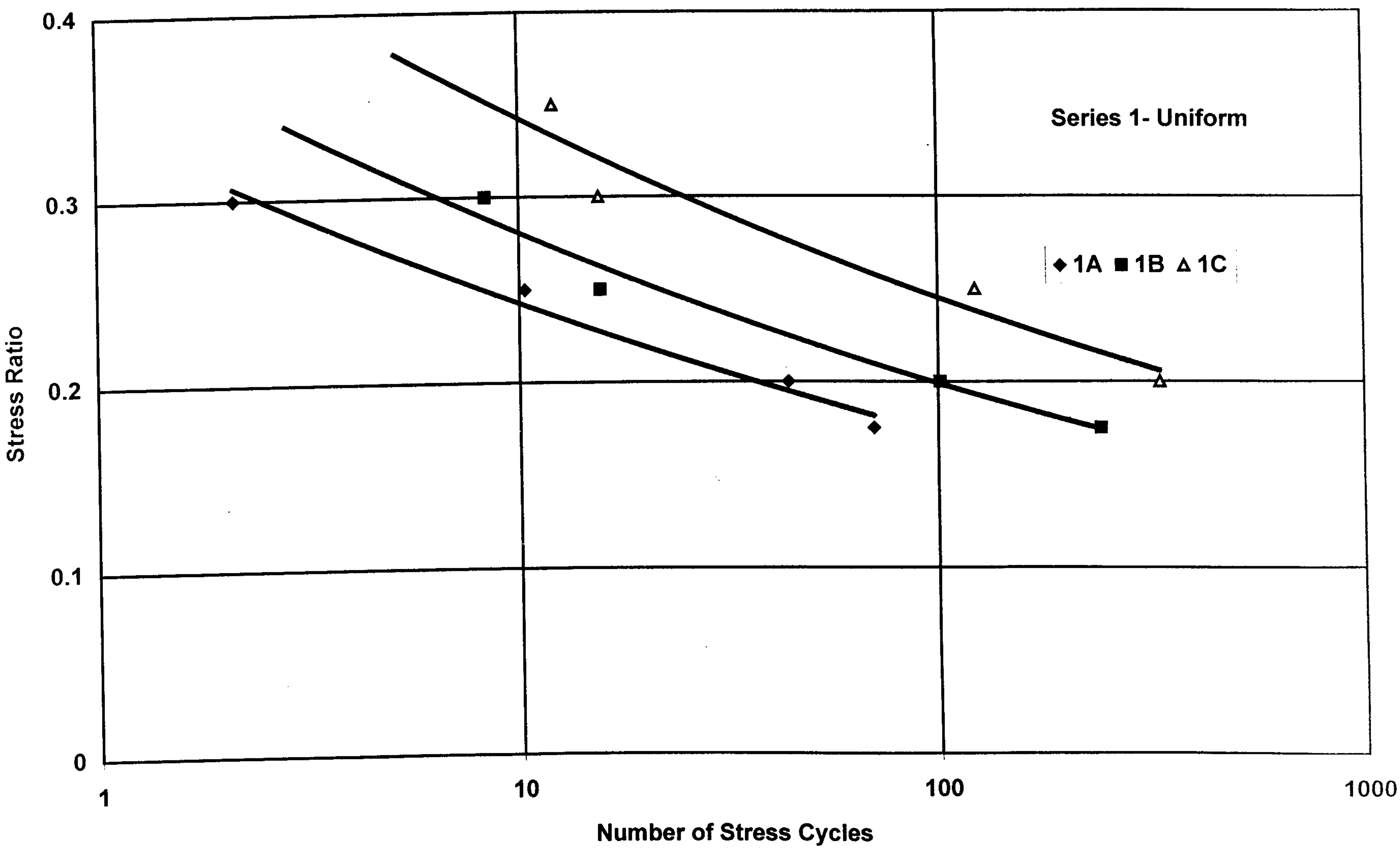


Figure 4. Effect of Silt Content on Liquefaction of Uniform Soils; Series 1; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1a for Soils Description)

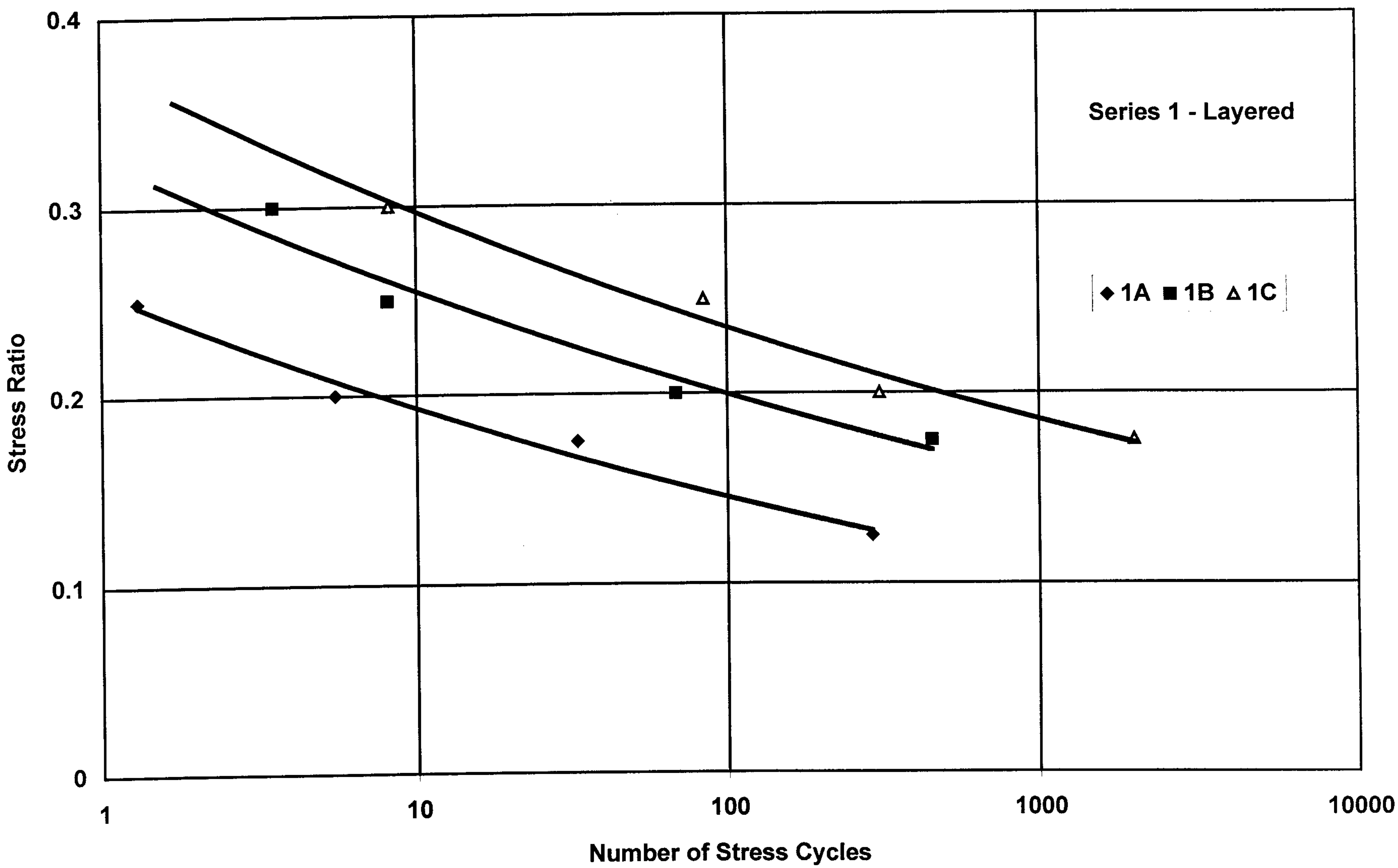


Figure 5. Effect of Silt Content on Liquefaction of Layered Soils; Series 1; Confining Pressure = 100 KPa (See Table 1a for Soils Description)

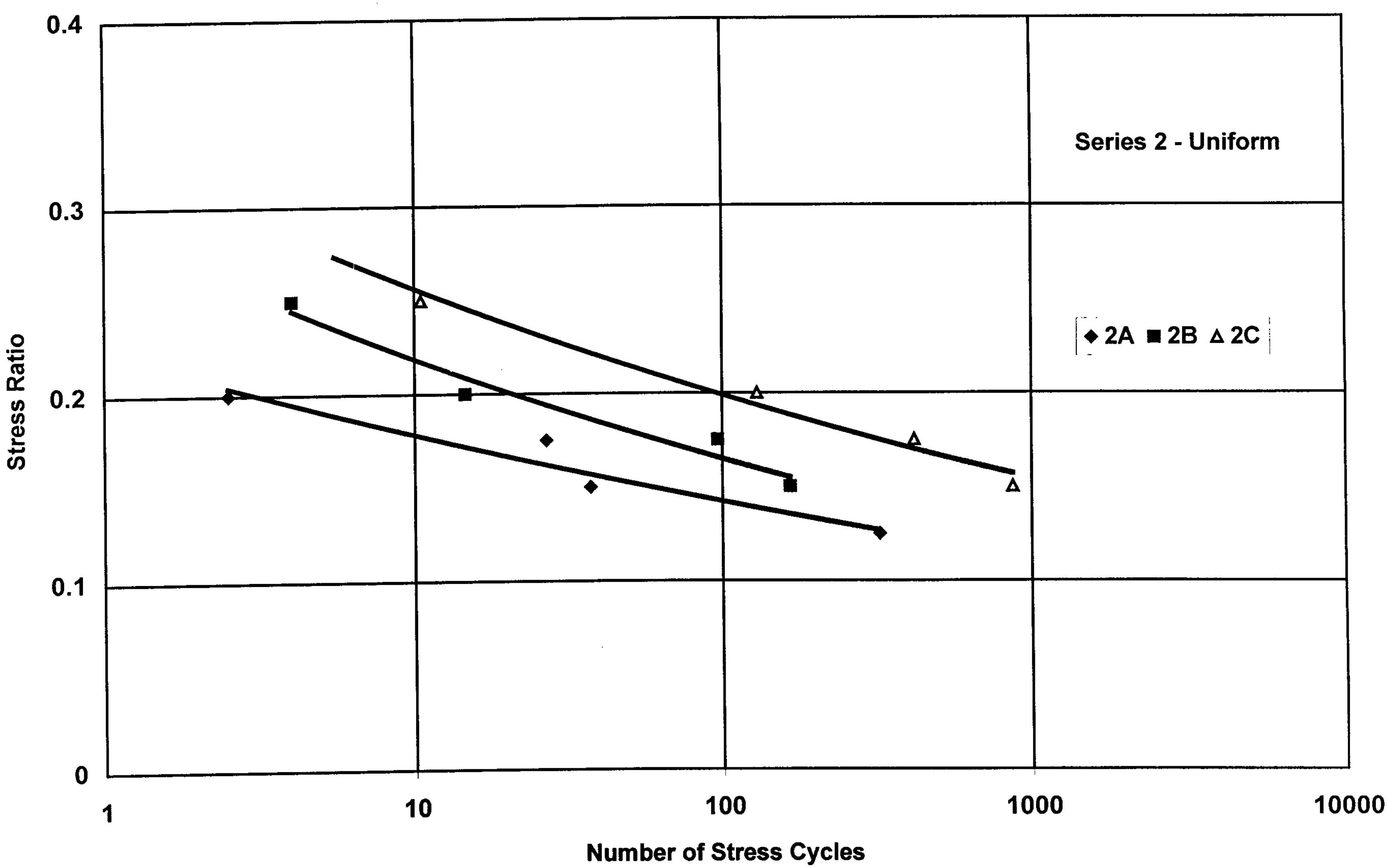


Figure 6. Effect of Silt Content on Liquefaction of Uniform Soils; Series 2; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1b for Soils Description)

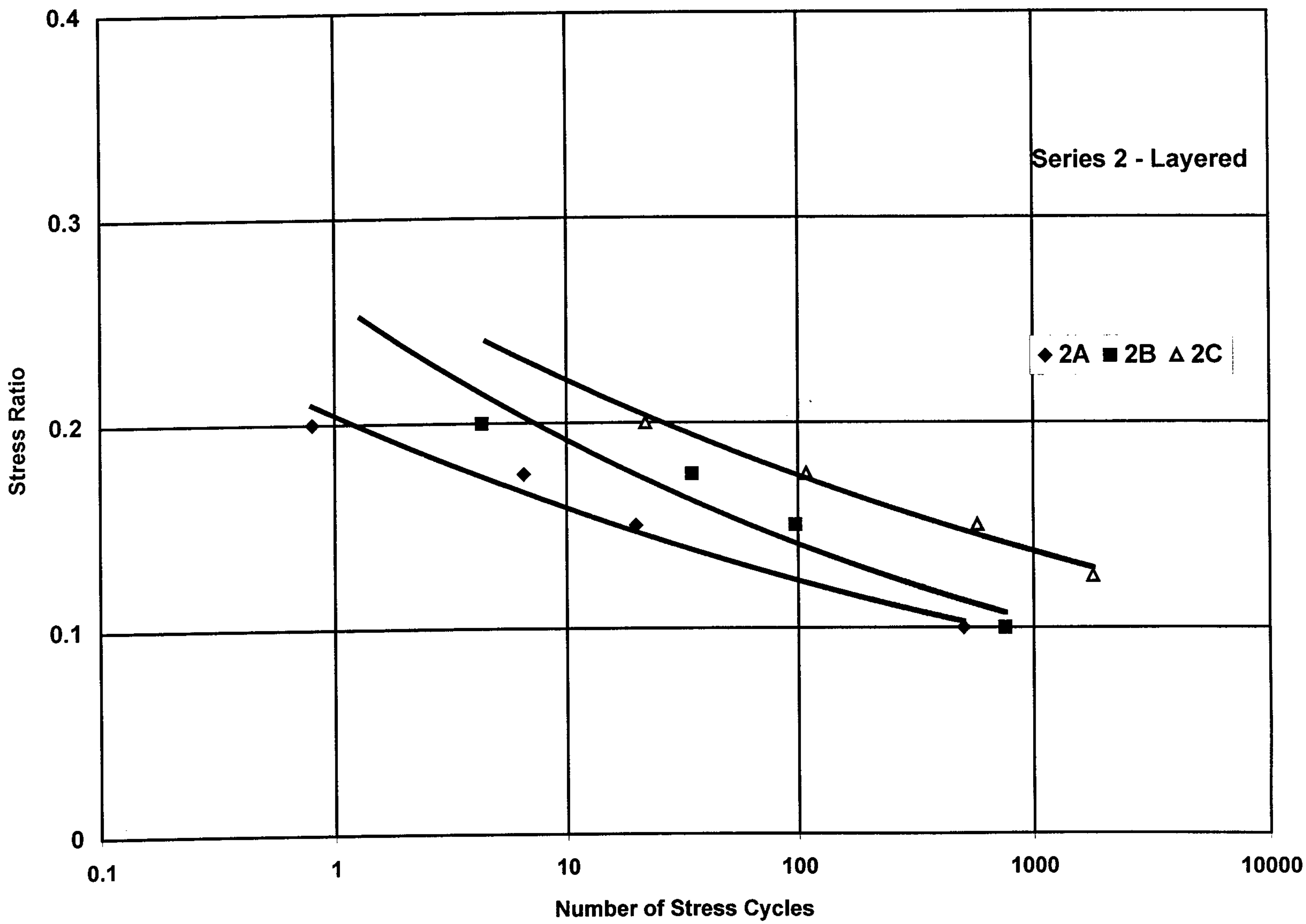


Figure 7. Effect of Silt Content on Liquefaction of Layered Soils; Series 2; Confining Pressure = 100 KPa (See Table 1b for Soils Description)

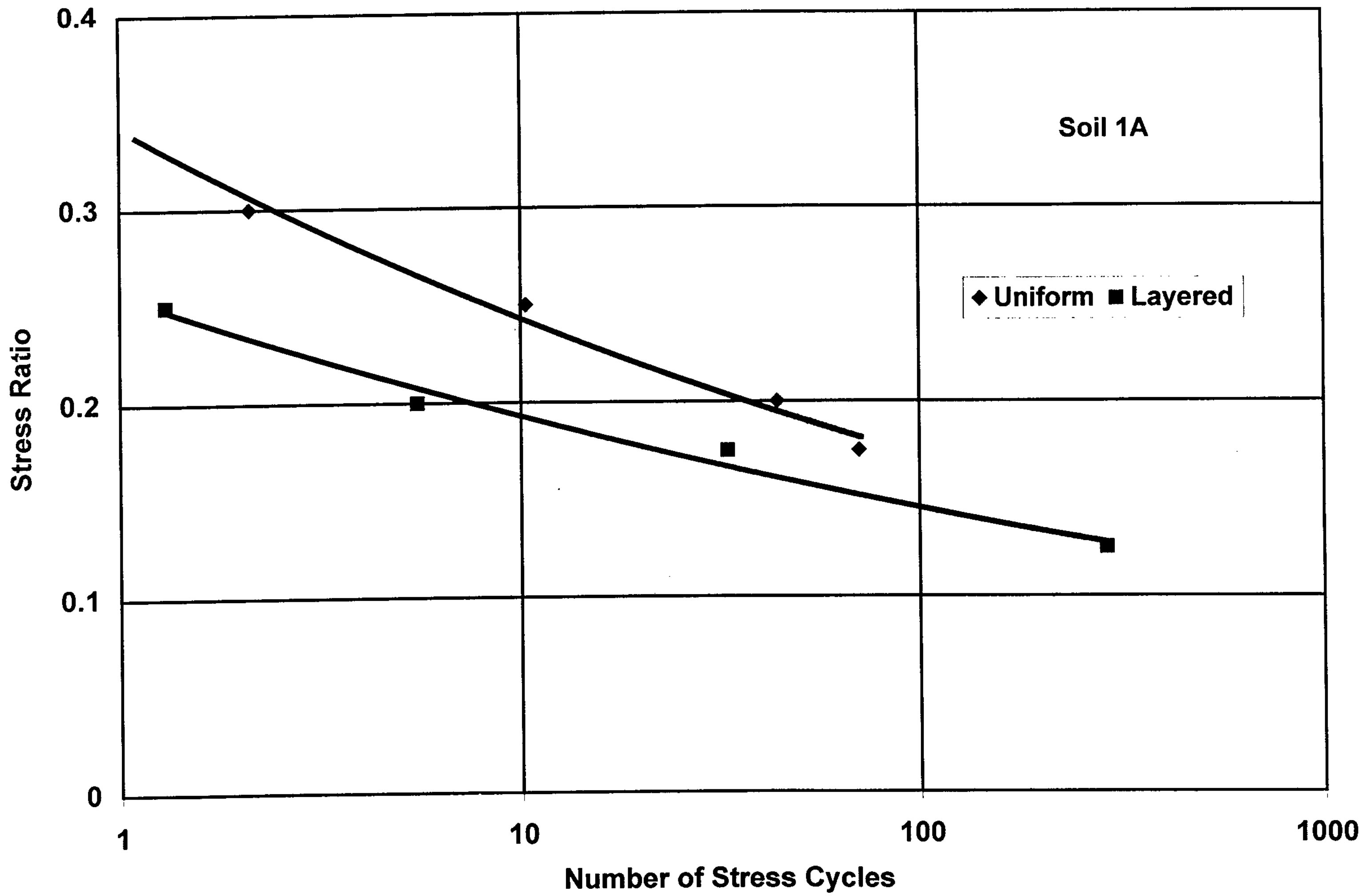


Figure 8. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 1A; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1a for Soils Description)

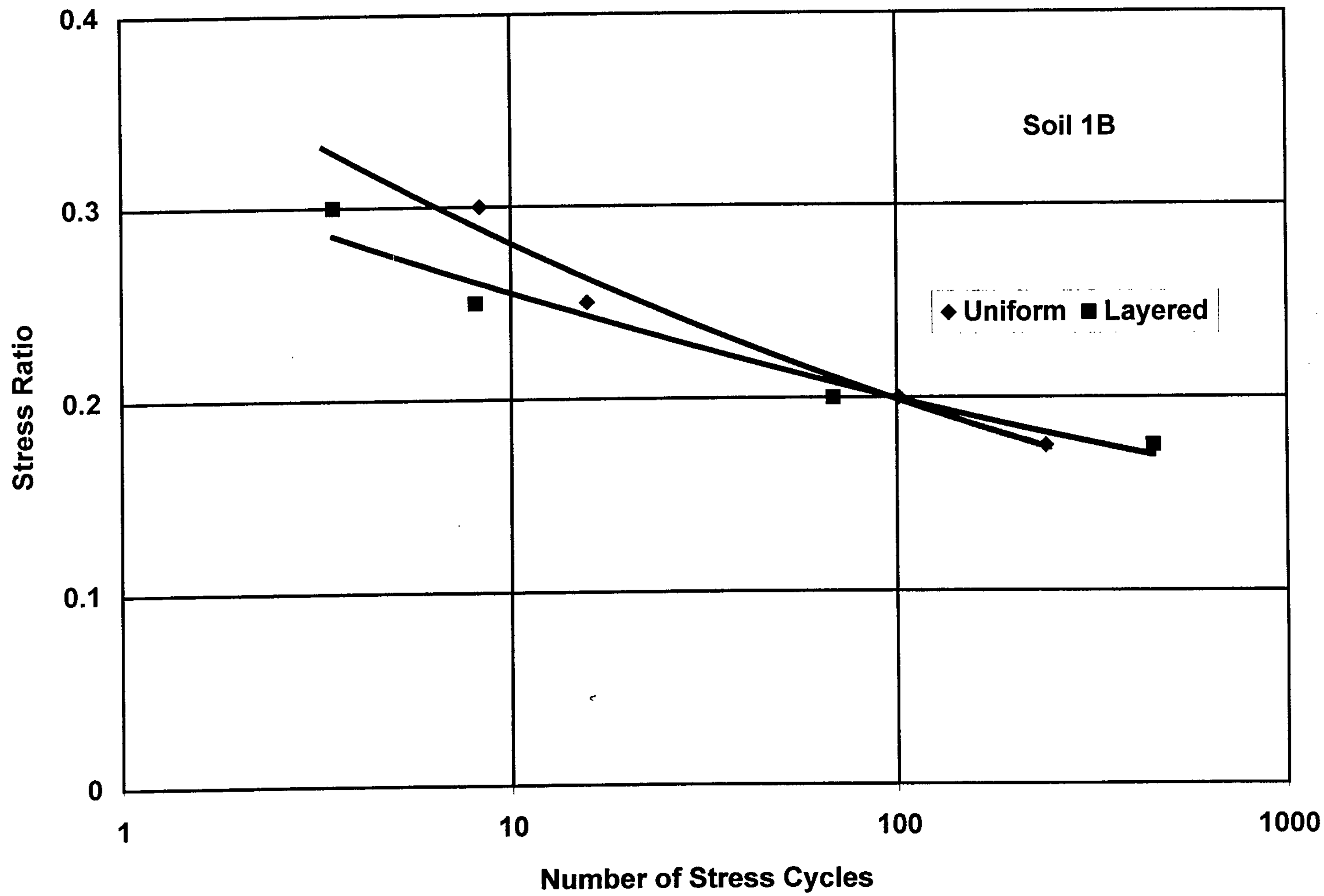


Figure 9. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 1B; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1a for Soils Description)

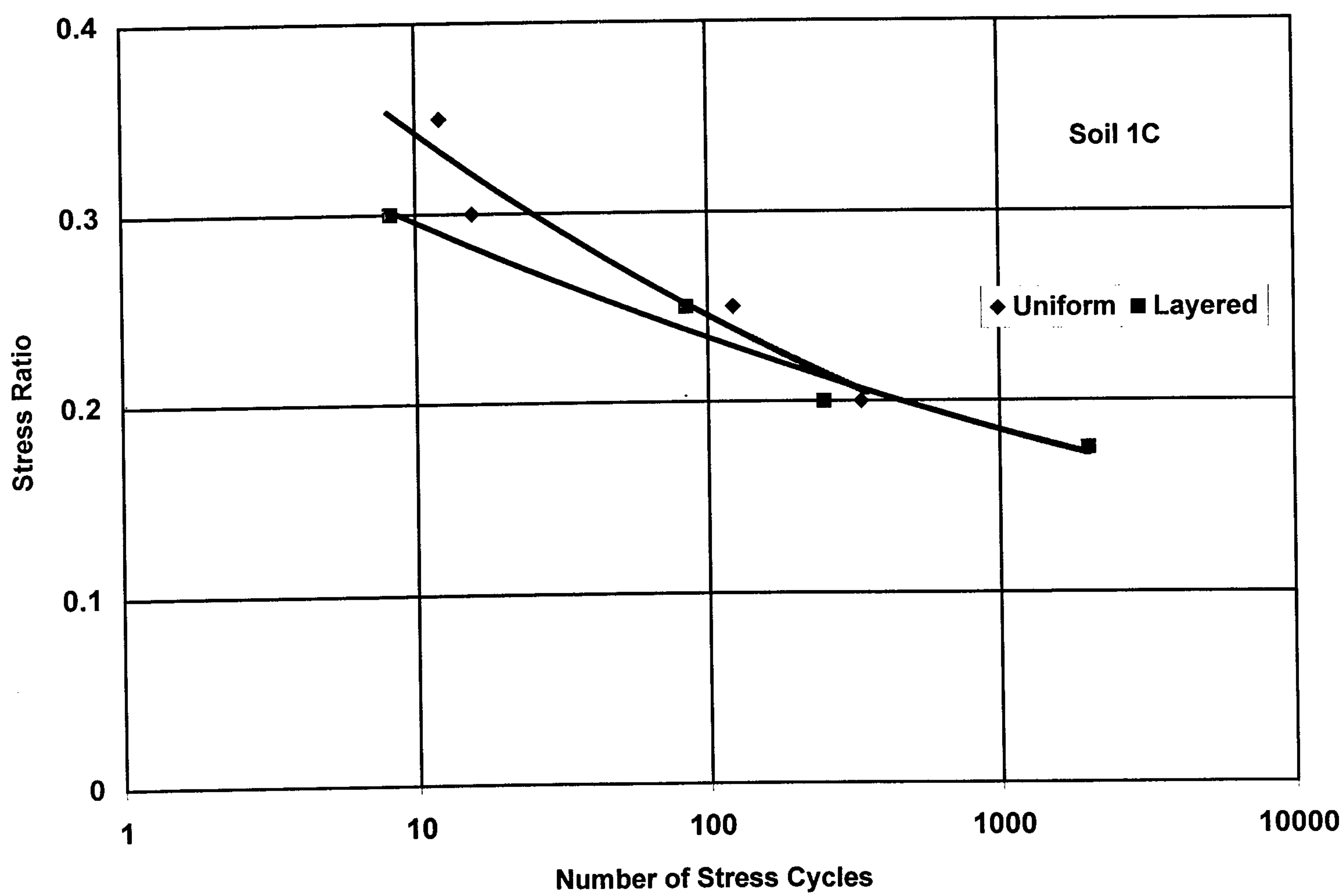


Figure 10. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 1C; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1a for Soils Description)

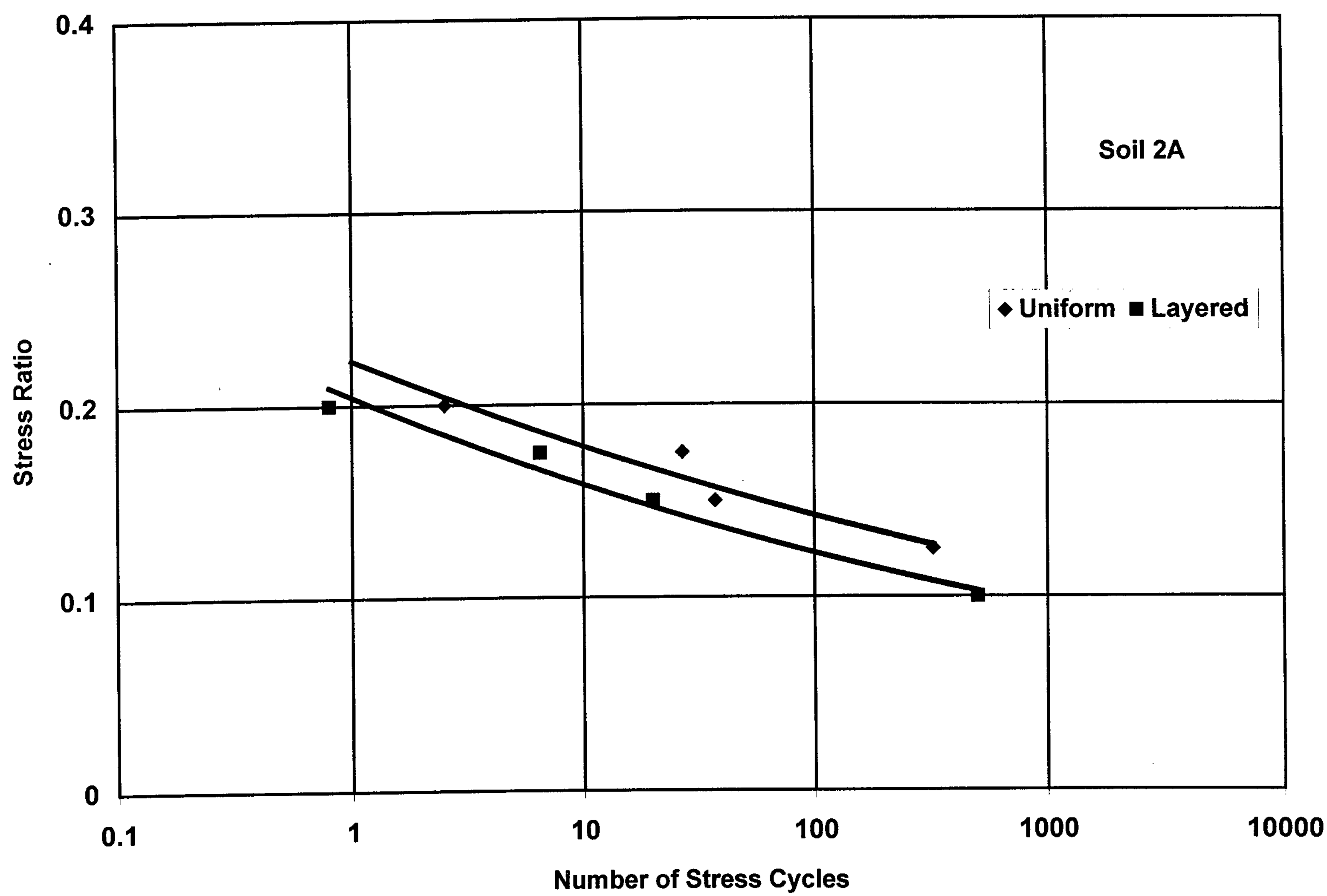


Figure 11. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 2A; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1b for Soils Description)

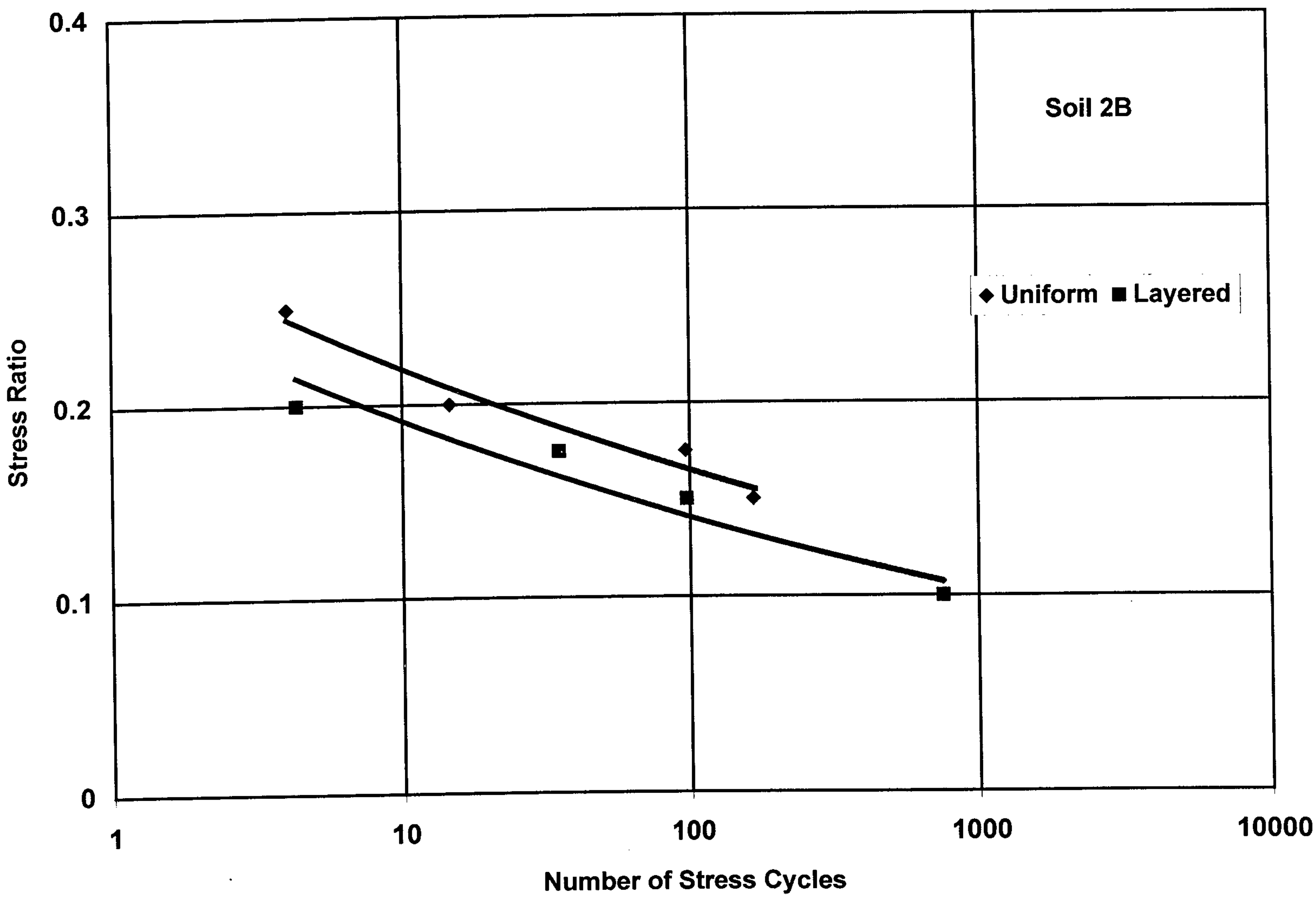


Figure 12. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 2B; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1b for Soils Descrition)

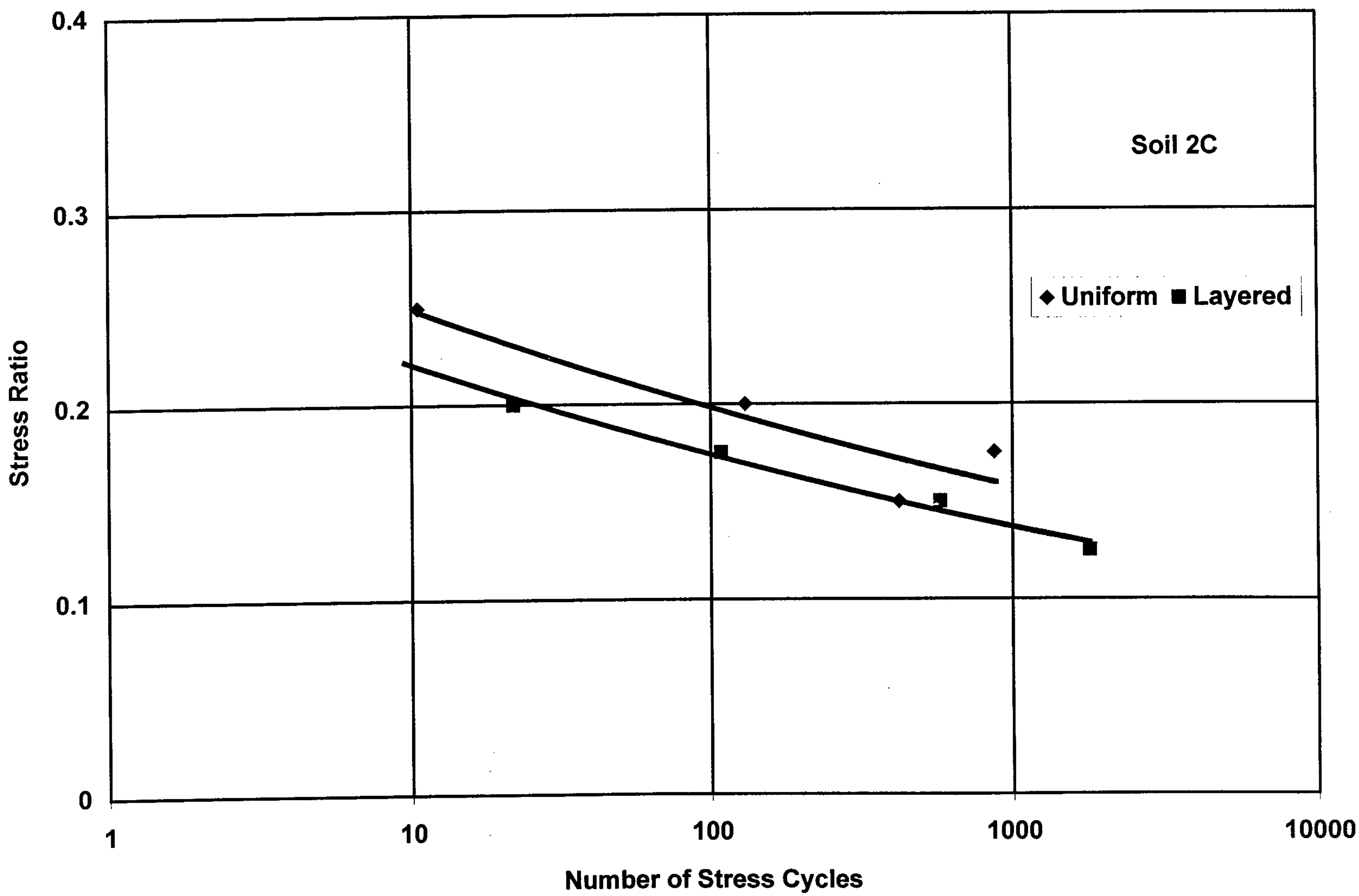


Figure 13. Comparison between Liquefaction Behavior of Layered and Uniform Soils, Soil 2C; $D_r$ = 50%; Confining Pressure = 100 KPa (See Table 1b for Soils Description)

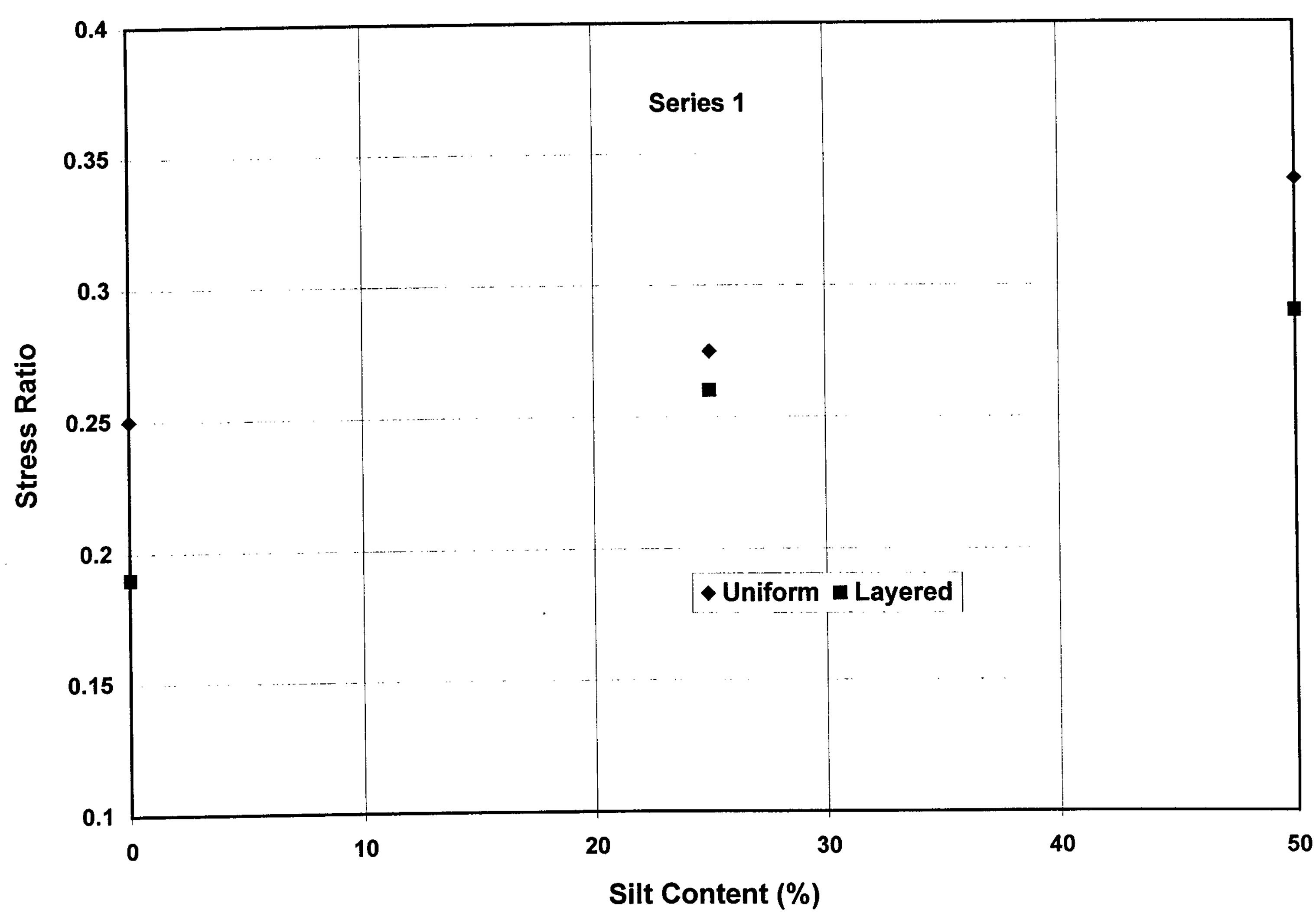


Figure 14. Comparison between Liquefaction Behavior of Layered and Uniform Soils as a Function of Silt Content; No. of Stress Cycles = 10; $D_r$ = 50%; Confining Pressure = 100 KPa

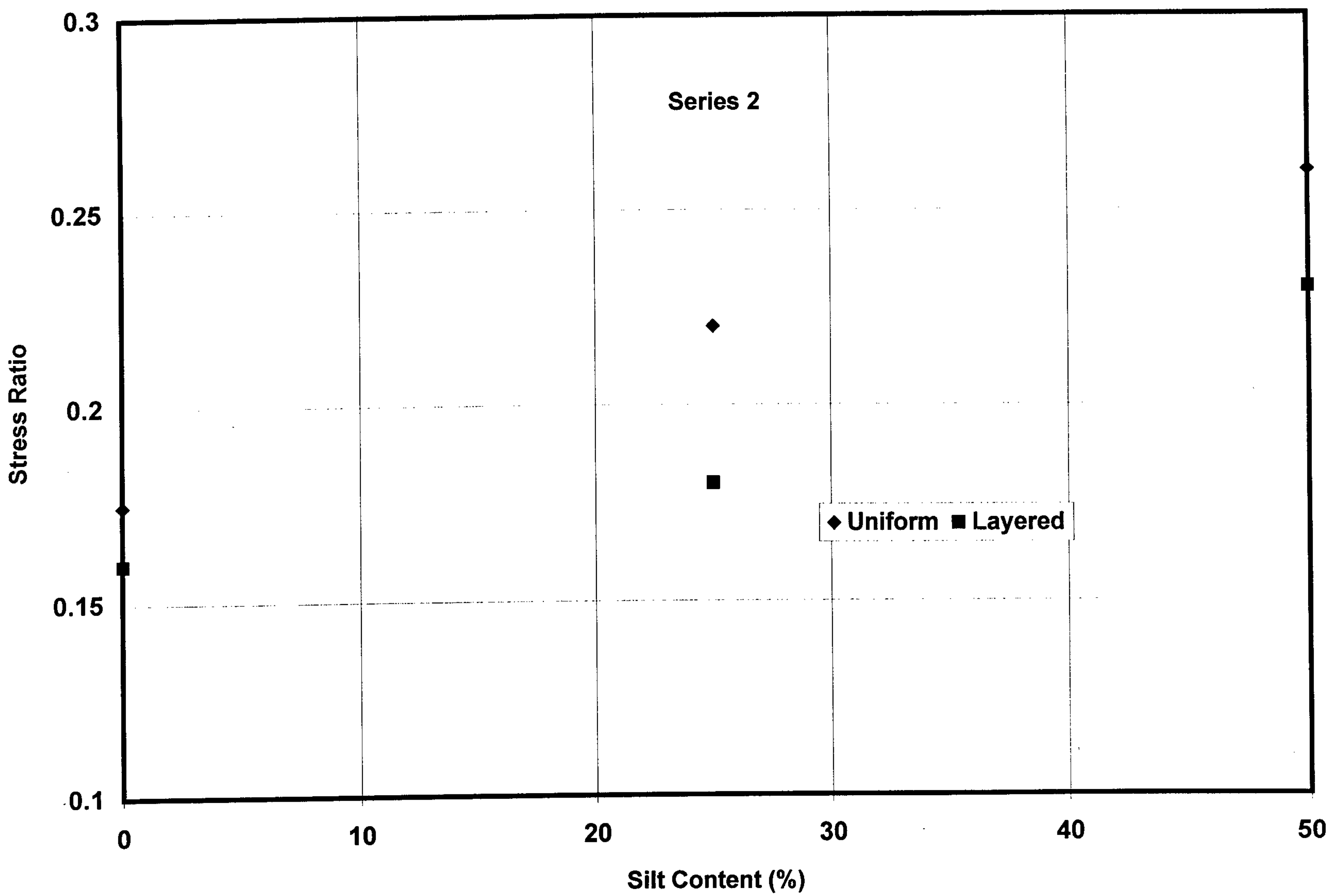


Figure 15. Comparison between Liquefaction Behavior of Layered and Uniform Soils as a unction of Silt Content; No. of Stress Cycles = 10; $D_r$ = 50%; Confining Pressure = 100 KPa

soils of series 2 (10% gravel), the net difference in resistance was almost constant resulting in parallel (Stress Ratio vs. Number of Cycles) curves. The highest difference in cyclic stress ratio causing liquefaction after 10 cycles was approximately 20%, and was observed in soils of Group 1A (30% gravel, 70% sand).

Examples of pore water pressure buildup curves for the layered and uniform soil conditions are shown in Figure 16 and 17, and the complete data for these examples are shown in Appendix II. As shown in Figures 16 and 17, the pore water pressure buildup curves for the two methods of sample preparation are similar. The pore water pressure buildup characteristics and liquefaction resistance of the silty sandy gravely soils are not significantly affected by the fabric of soil specimen. In layered soils, the permeability in horizontal direction is significantly higher than the vertical permeability. This also implies that excess pore water pressure will extend faster in the horizontal direction than a vertical direction. In addition, results using centrifuge model tests suggest that during liquefaction a water interlayer or very loose zone of soil may develop at the sand-silt interface due to the difference in permeabilities. Nevertheless, this similarity between behavior of homogeneous and layered soils was observed for a range of silt and gravel contents. It should also be noted that although the uniform and layered specimens may have similar pore water pressure buildup characteristics, the one than can expel more water to the surrounding soils is more hazardous if we consider the entire soil system. Additional research is therefore required to shed further light and to clarify the amounts of water generated by reconsolidation of the uniform and layered complex system of these silty sandy gravely soils. Furthermore, investigation of microstructural features of stratified soils and their relations to the dynamic macro behavior will help to provide further understanding of behavior of the layered soils. New research should cover a wide range of variables including confining pressures, gravel contents, and anisotropic soil conditions.

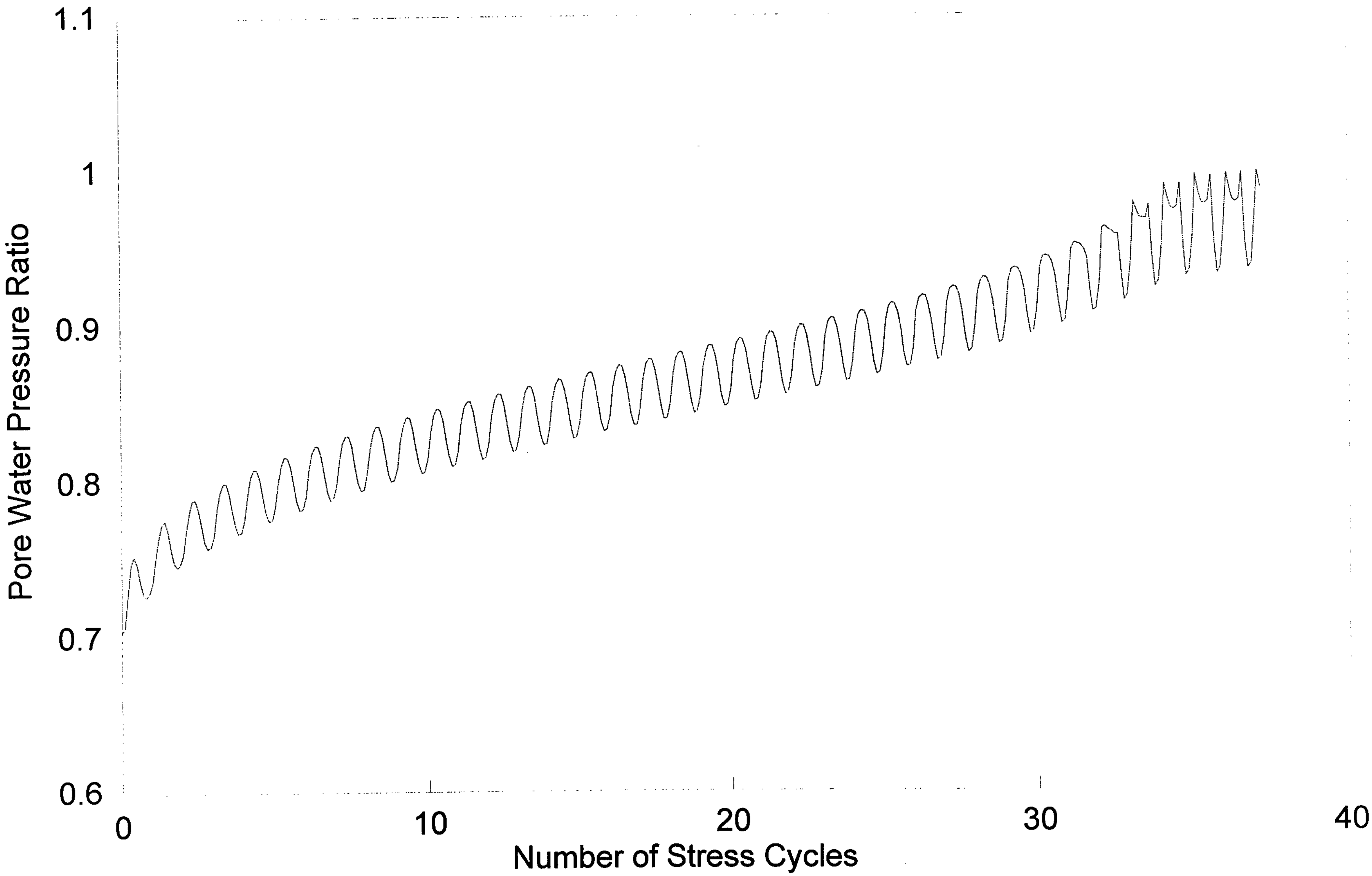


Figure 16. Pore Water Pressure Buildup Curve for Uniform Soil Conditions, Soil 2A; Confining Pressure=100 KPa; $D_r$ = 50% (See Table 1b for Soils Description)

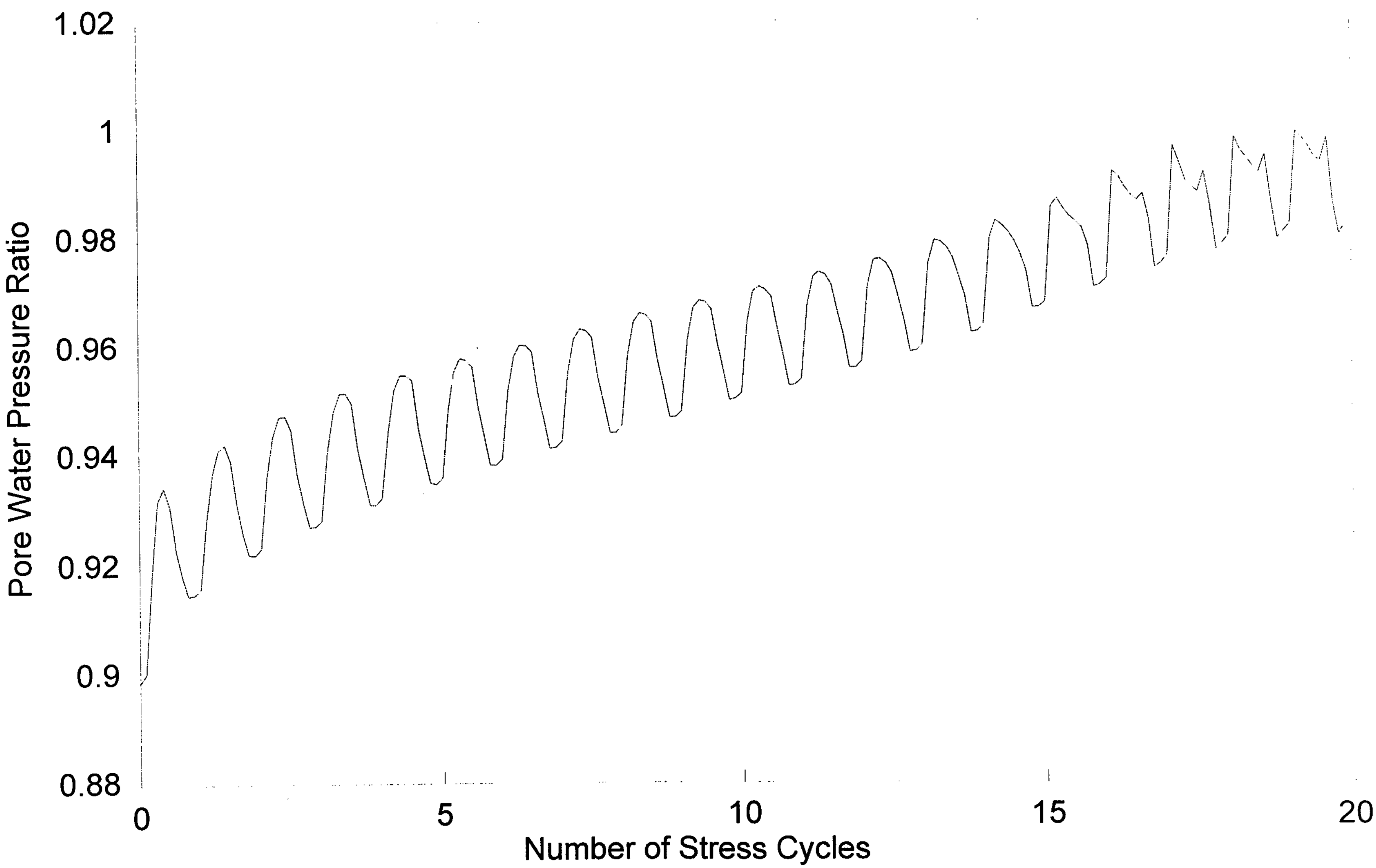


Figure 17. Pore Water Pressure Buildup Curve for Layered Soil Conditions, Soil 2A; Confining Pressure = 100 KPa; $D_r$ = 50% (See Table 1b for Soils Description)

## 5. CONCLUSIONS

A preliminary experimental program to study the behavior of layered soil conditions was undertaken in which a total of fifty stress-controlled cyclic triaxial tests were performed on sand-silt-gravel composites. The following primary conclusions were obtained as a result of this study.

1. The liquefaction resistance of layered and uniform soils are not significantly different, despite the fact that the soil fabric produced by the two methods of sample preparation is totally different. This behavior was observed for silt content ranging from 0 to 50 percent, and gravel content of 10 and 30 percent. This finding justifies applying the laboratory tests results to the field conditions for the range of variable studied.
2. The increase in silt content (percent passing No. 200 sieve) causes the liquefaction resistance of sand-silt-gravel mixtures to increase for both uniform and layered soil conditions.

More research is needed to confirm these findings for a wide range of variables including confining pressures, gravel contents, and anisotropic soil conditions.

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APPENDIX I

## STUDENTS SUPPORTED BY THIS PROJECT AND DEGREES AWARDED

1. Kossi Sama, B.S., Civil Engineering, May 1998
2. Pablo Gonzalez, B.S., Civil Engineering, May 1998
3. Veronica Ghelardi, B.S., Civil Engineering, December1998 (expected)

## LIST OF MANUSCRIPTS PUBLISHED UNDER AFOSR SPONSORSHIP DURING THE REPORTING PERIODS

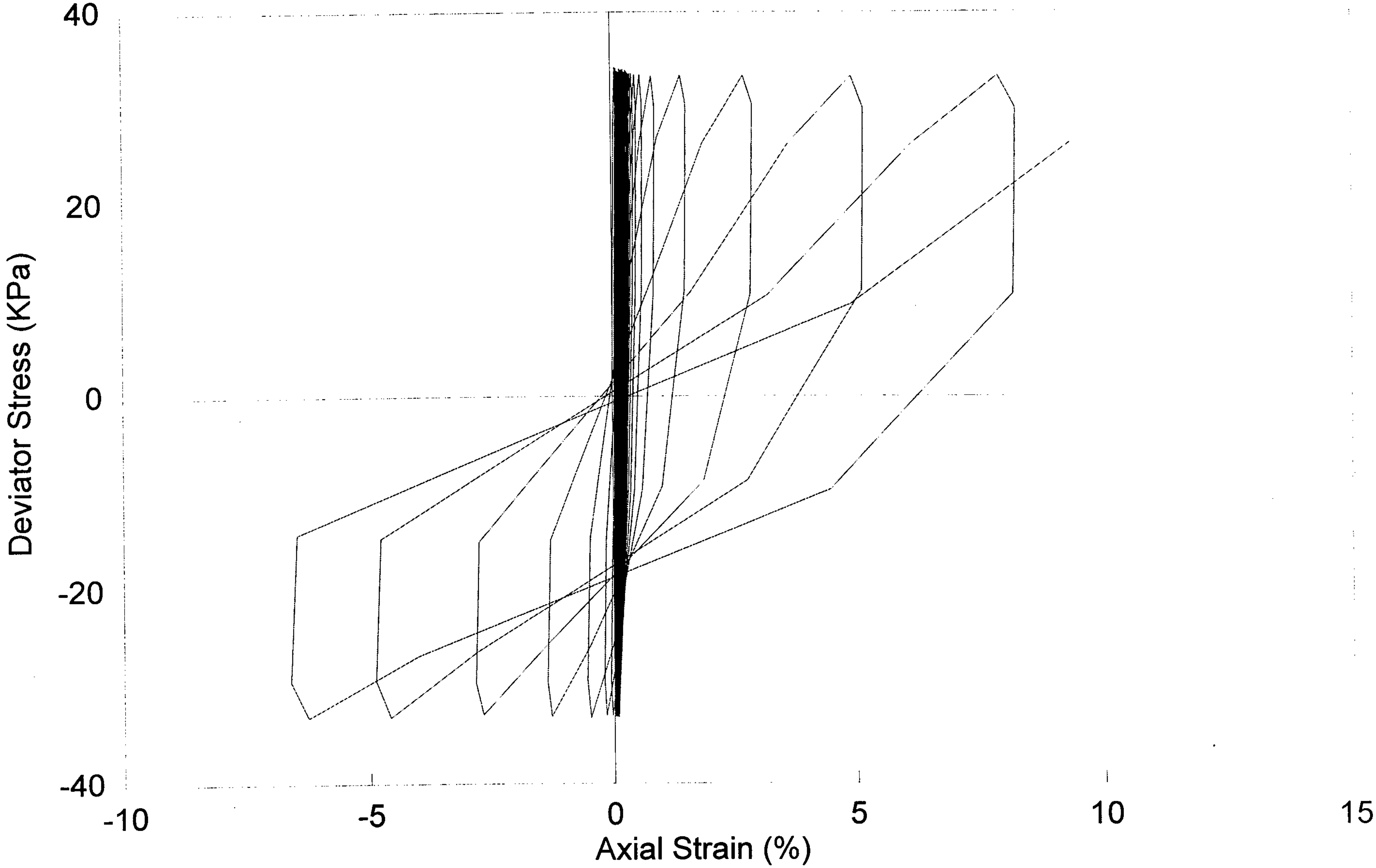
Research has recently been completed. Manuscripts will be prepared for publication. They will be sent shortly.

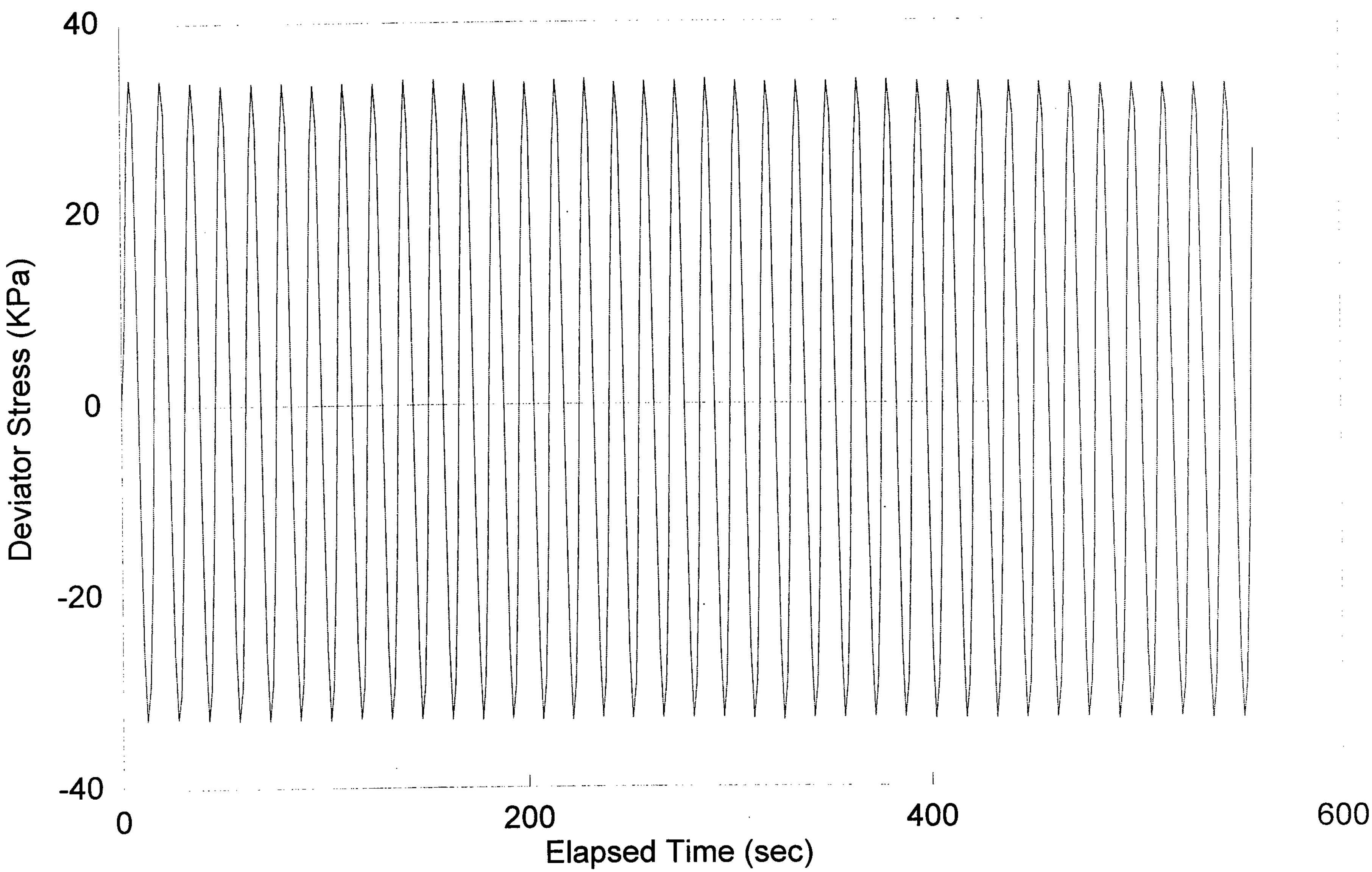
## REPORT OF INVENTION

None

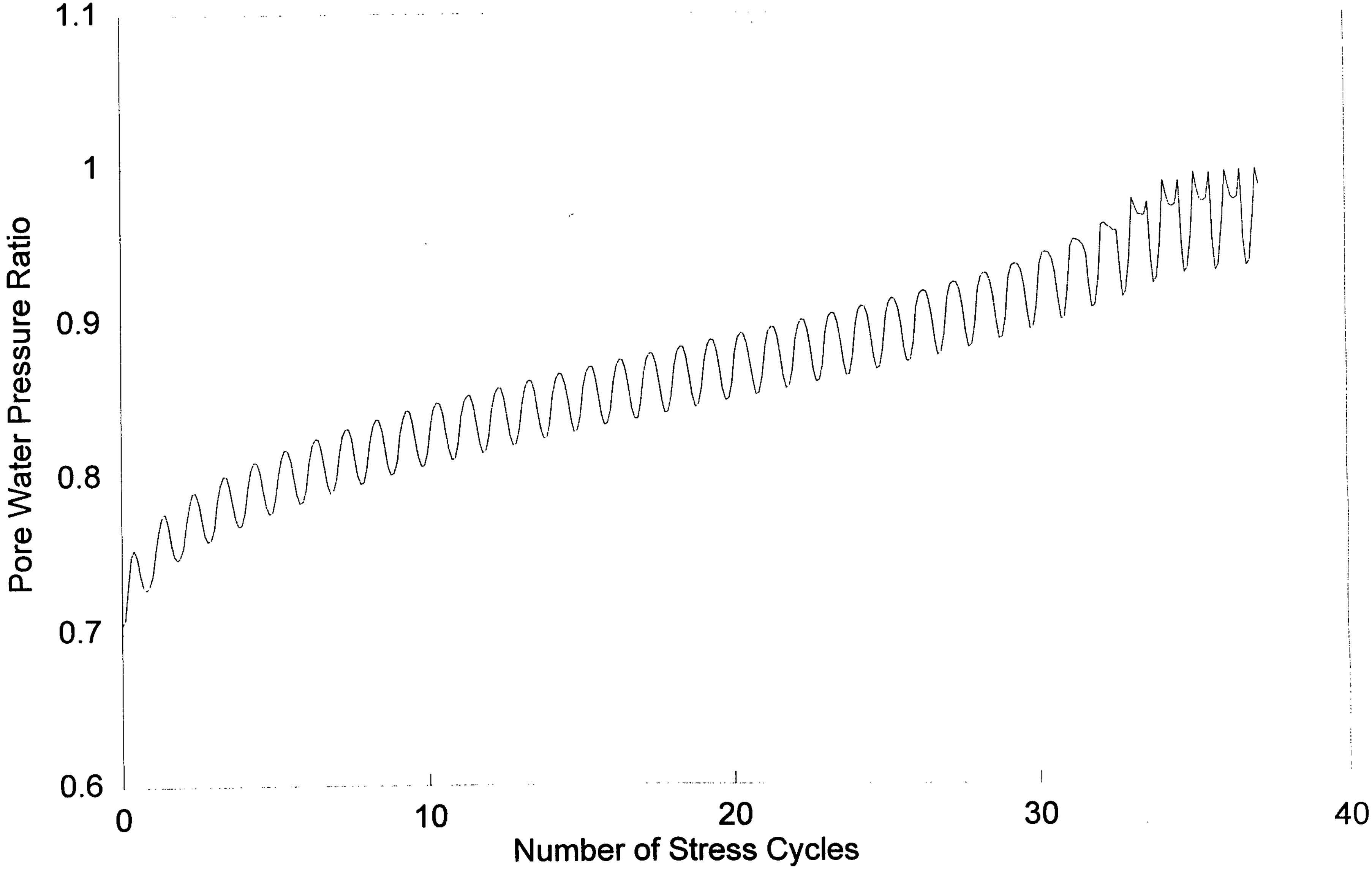
APPENDIX II

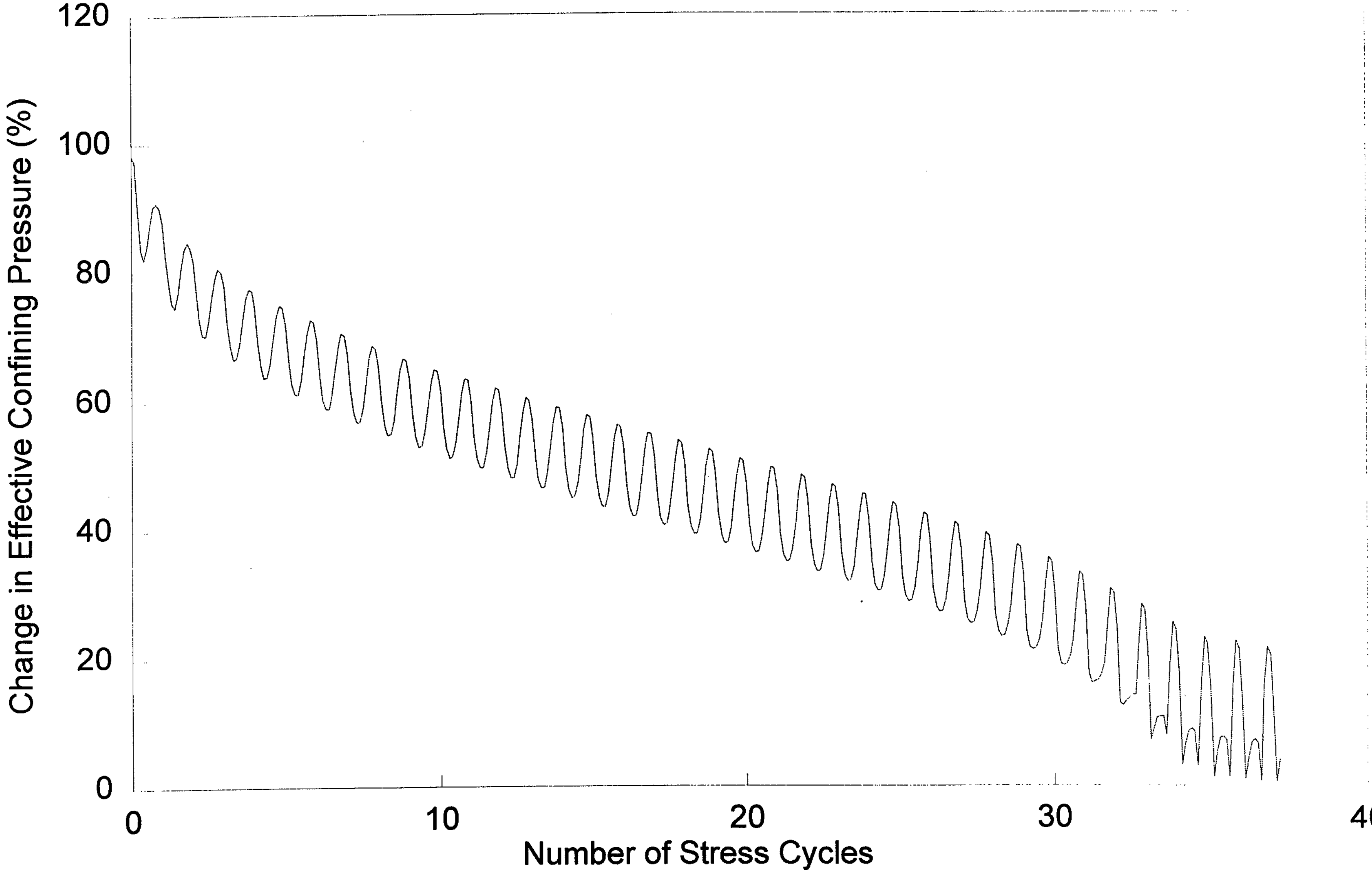
EXAMPLES OF DATA: UNIFORM CONDITION. SOIL 2A:
10% GRAVEL, 25%SILT, 65% SAND.
EFFECTIVE CONFINING PRESSURE = 100 KPa; Dr = 50%


Deviator Stress (KPa)
40
20
0
-20
-40
-10
-5
0
5
10
15
Axial Strain (%)

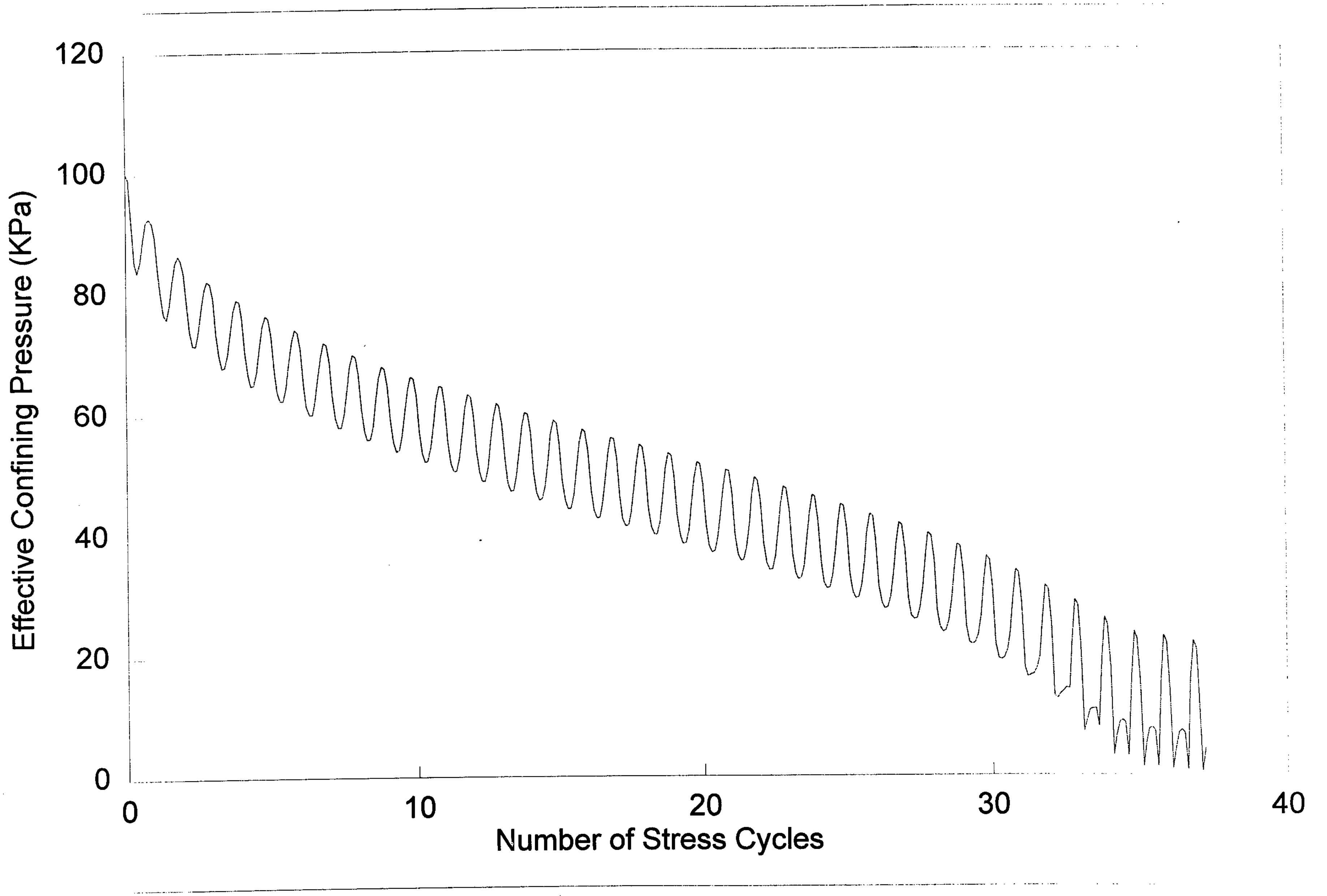


Deviator Stress (KPa)
40
20
0
-20
-40
0
200
400
600
Elapsed Time (sec)


1.1
1
0.9
0.8
0.7
0.6
Pore Water Pressure Ratio
0
10
20
30
40
Number of Stress Cycles

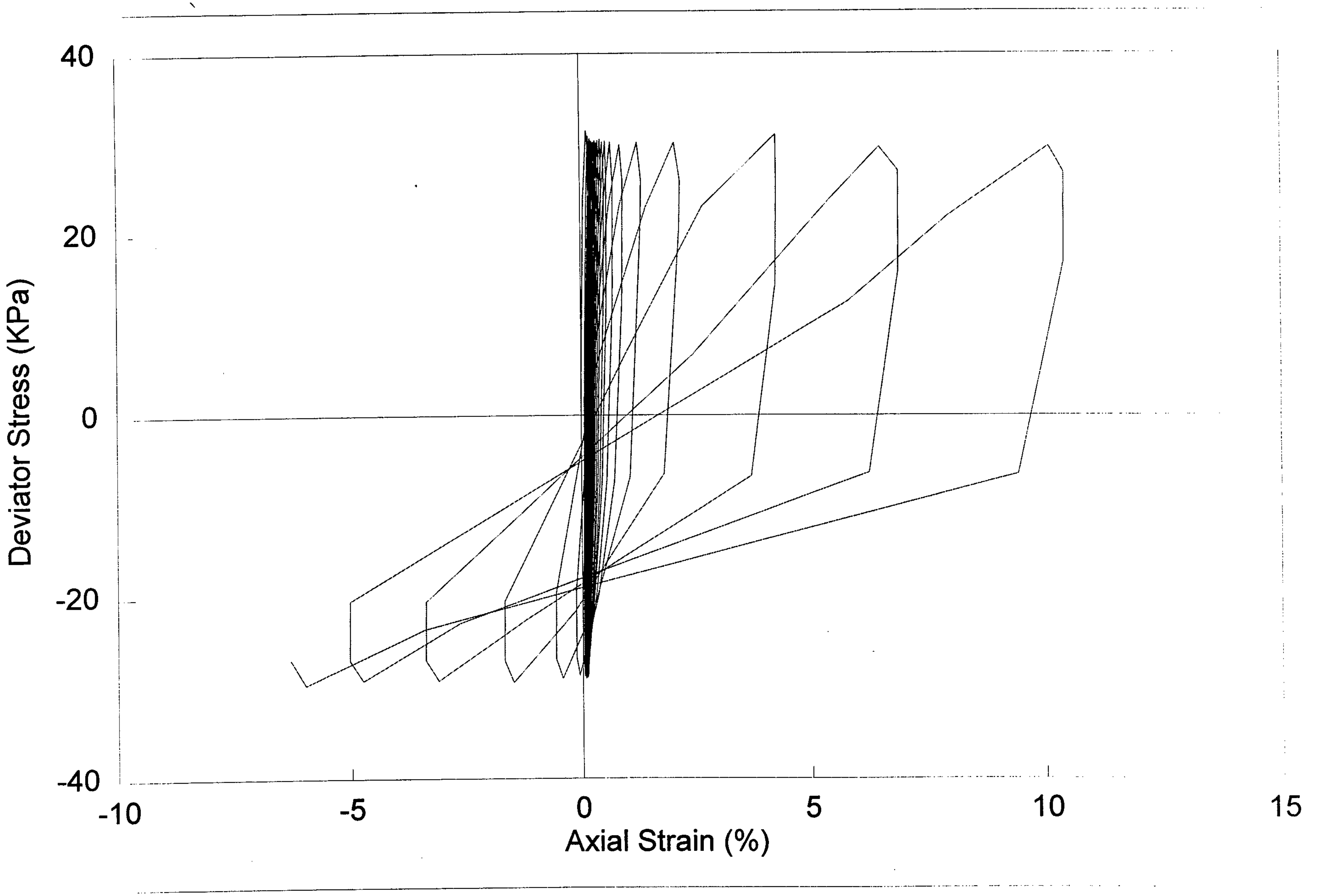


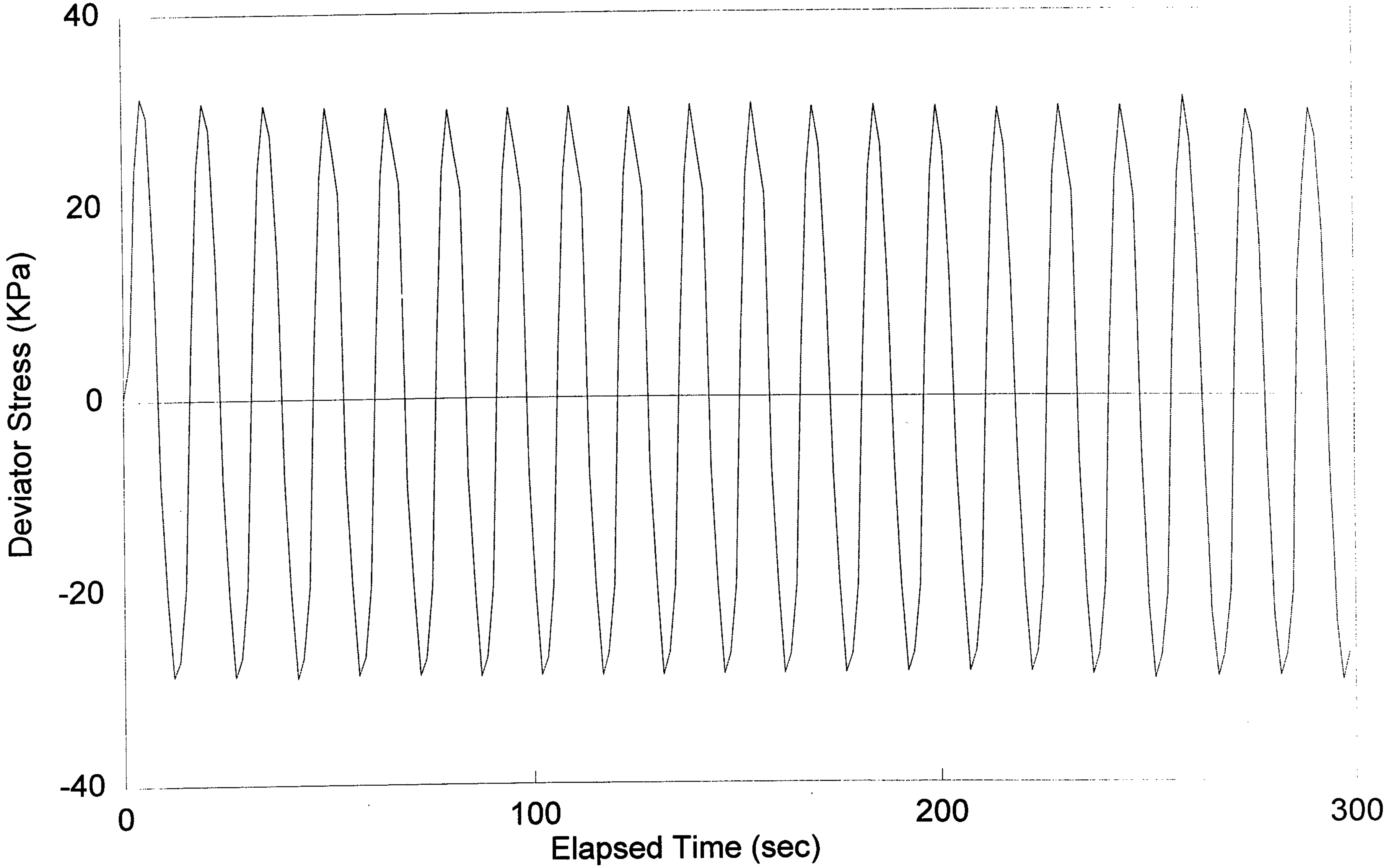
Change in Effective Confining Pressure (%)
120
100
80
60
40
20
0
0
10
20
30
40
Number of Stress Cycles



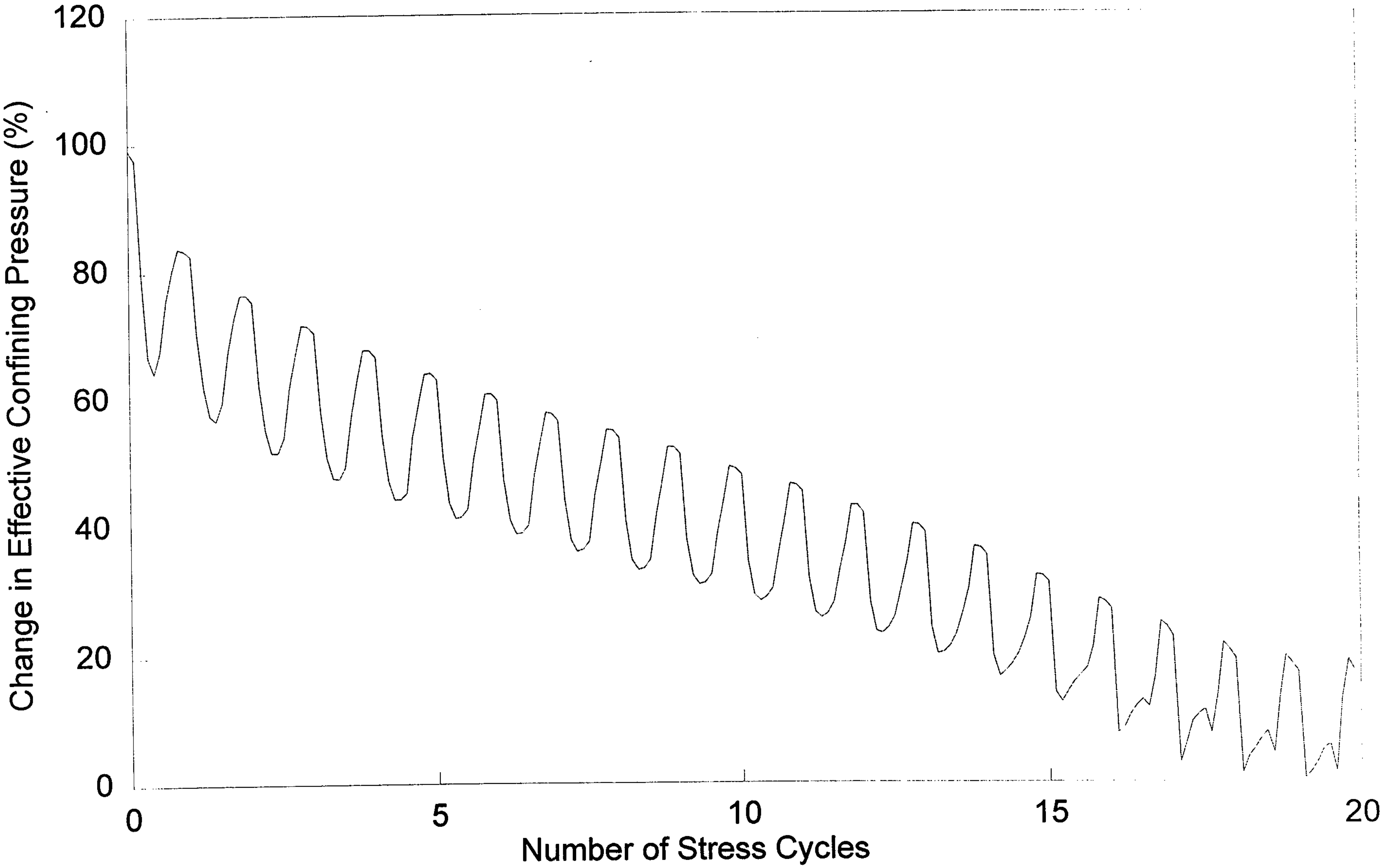
Effective Confining Pressure (KPa)
120
100
80
60
40
20
0
0
10
20
30
40
Number of Stress Cycles

EXAMPLES OF DATA: LAYERED CONDITION. SOIL 2A:
10% GRAVEL, 25%SILT, 65% SAND.
EFFECTIVE CONFINING PRESSURE = 100 KPa; Dr = 50%

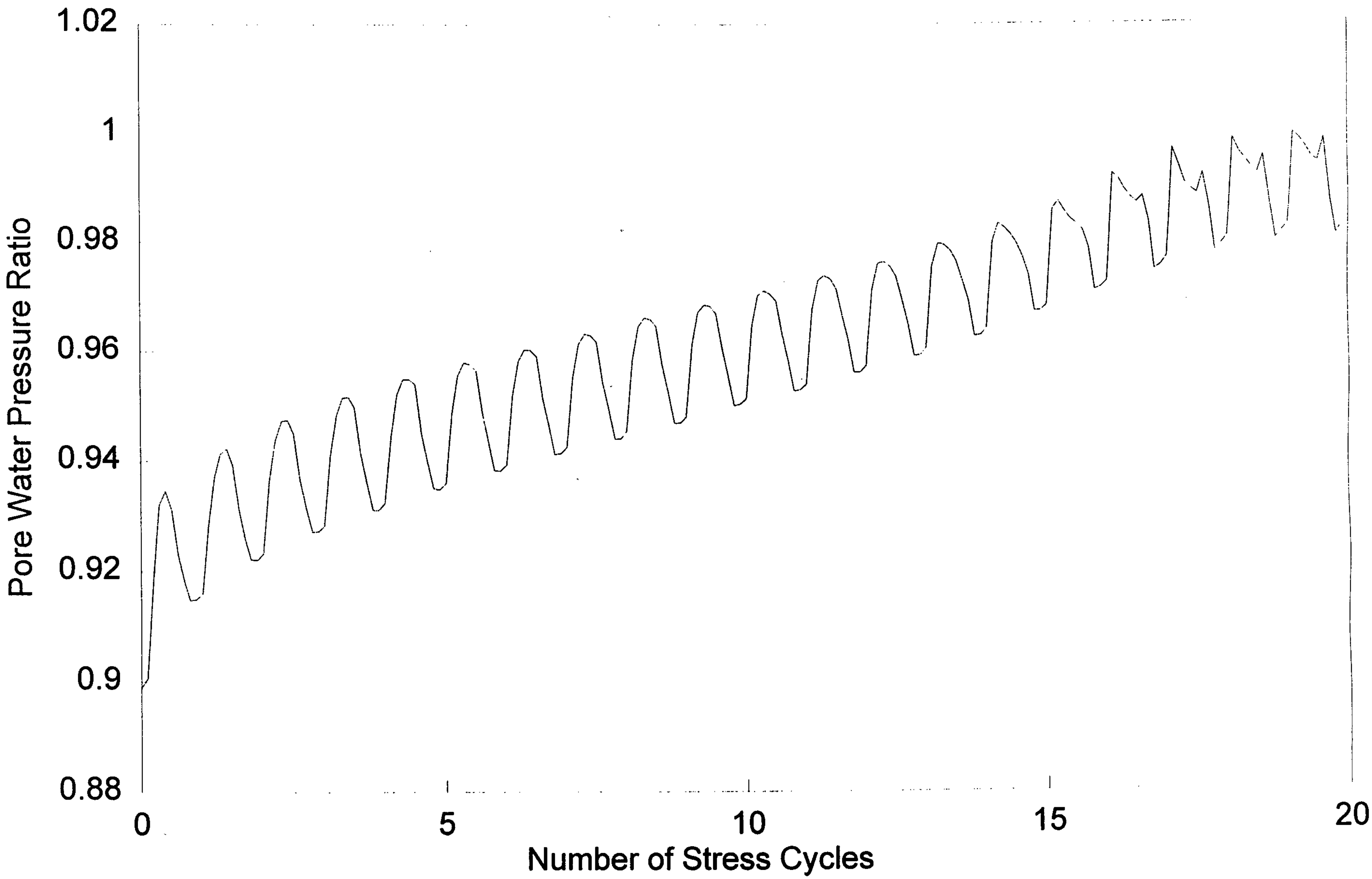

Deviator Stress (KPa)
40
20
0
-20
-40
-10
-5
0
5
10
15
Axial Strain (%)

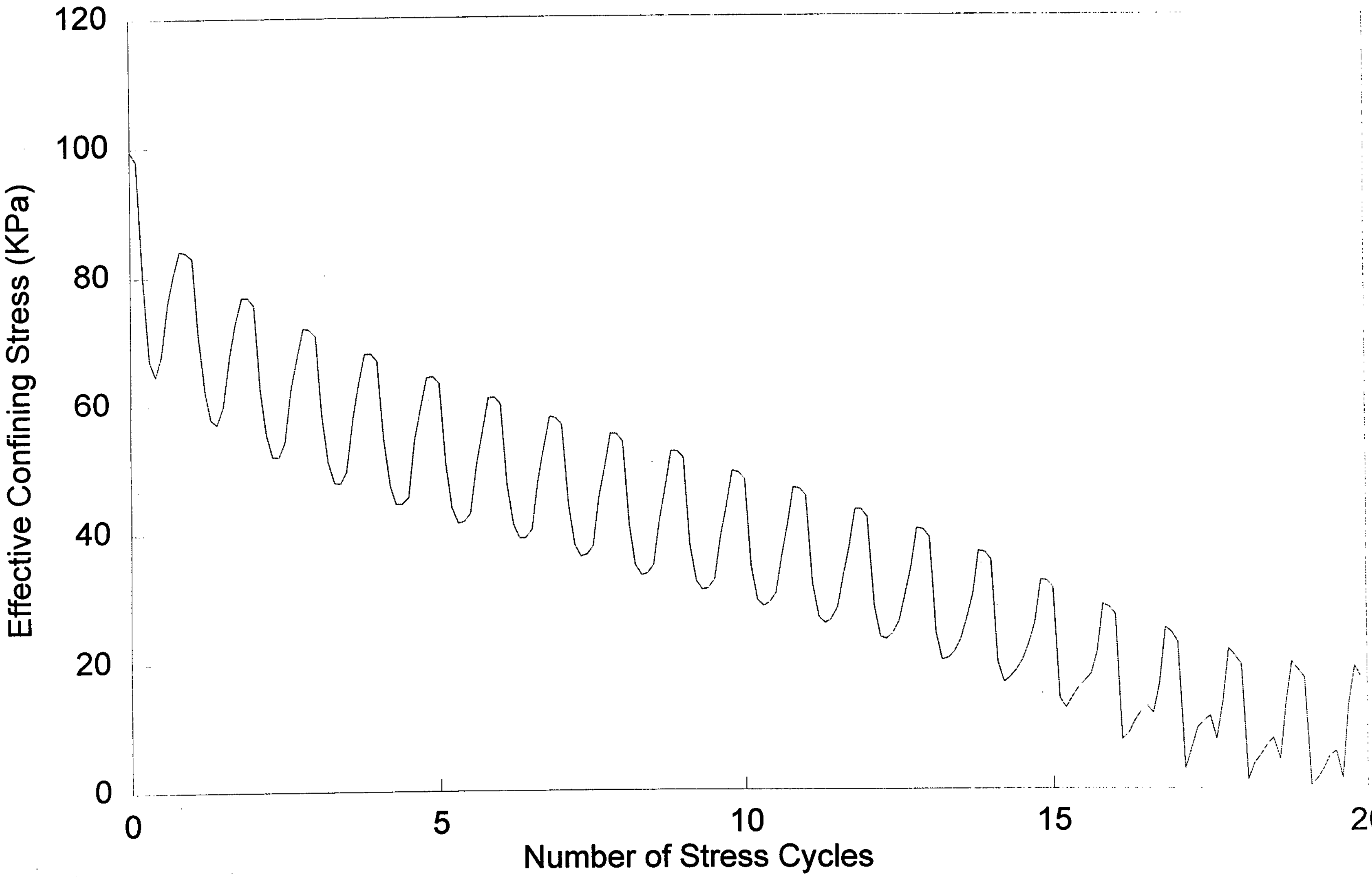


40
20
0
-20
-40
Deviator Stress (KPa)
0
100
200
300
Elapsed Time (sec)



Change in Effective Confining Pressure (%)
120
100
80
60
40
20
0
0
5
10
15
20
Number of Stress Cycles


Pore Water Pressure Ratio
1.02
1
0.98
0.96
0.94
0.92
0.9
0.88
0
5
10
15
20
Number of Stress Cycles



Effective Confining Stress (KPa)
120
100
80
60
40
20
0
0
5
10
15
20
Number of Stress Cycles